Status of the MINOS Experiment

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Outline

Introduction

Physics Goals

The NuMI Beam

MINOS Detectors

ν-induced Up-Going μ

Atmospheric Neutrinos

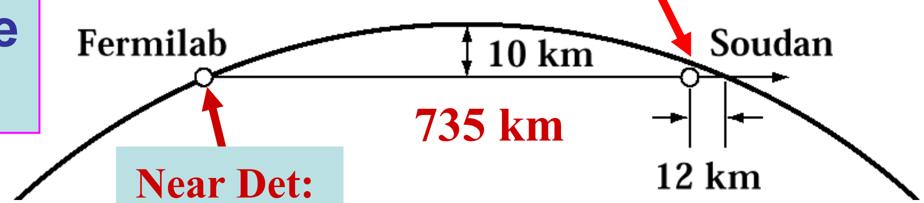
Accelerator Neutrino Data

Conclusions

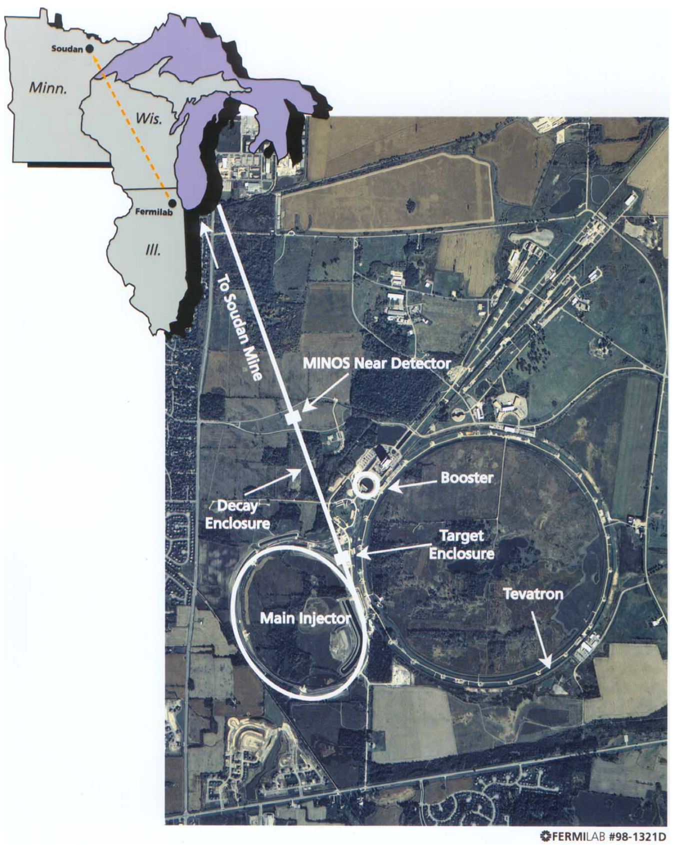
The MINOS Experiment

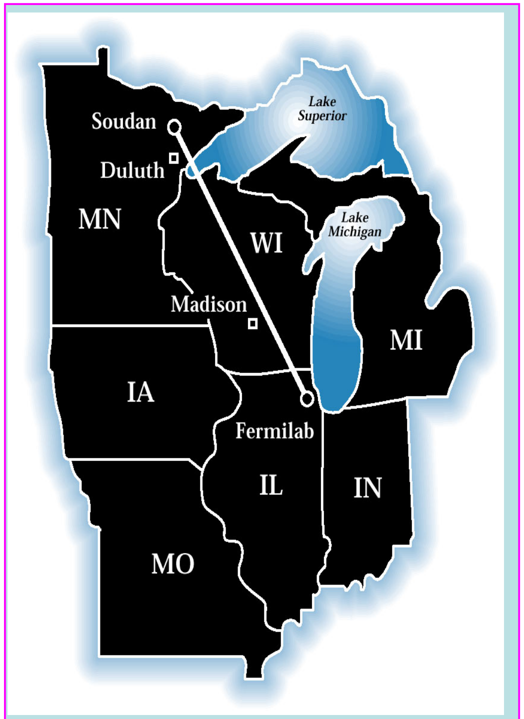
Precise study of “atmospheric” neutrino oscillations, using the NUMI beam and two detectors.

Far Det: 5400 tons



Near Det: 980 tons





Beam: NuMI beam, 120 GeV Protons $\rightarrow \nu_{\mu}$- beam

Detectors: ND, FD

Far Det: 5.4 kton magnetized Fe/Sci Tracker/Calorimeter at Soudan, MN (L=735 km)

Near Det: 980 ton version of FD, at FNAL (L $\approx$ 1 km)

MINOS Physics Goals

- **Demonstrate Oscillation Behavior**
  - Precise measurement of CC energy distribution between near and far detector. Confirm flavor oscillation description of data.
  - Disciminate against "Non-Standard" models: Decoherence, decay, extra dimensions ?
- **Precise Measurement of Oscillation Parameters:**
  Δm^2_{23} to $\sim$10%
- **Search for $\nu_\mu \leftrightarrow \nu_e$ oscillation:** First Measurement of θ_{13}?
- **First Direct Measurement of Atmospheric ν vs $\bar{\nu}$ oscillations:** The MINOS Far detector is the only large deep underground detector with a magnetic field.

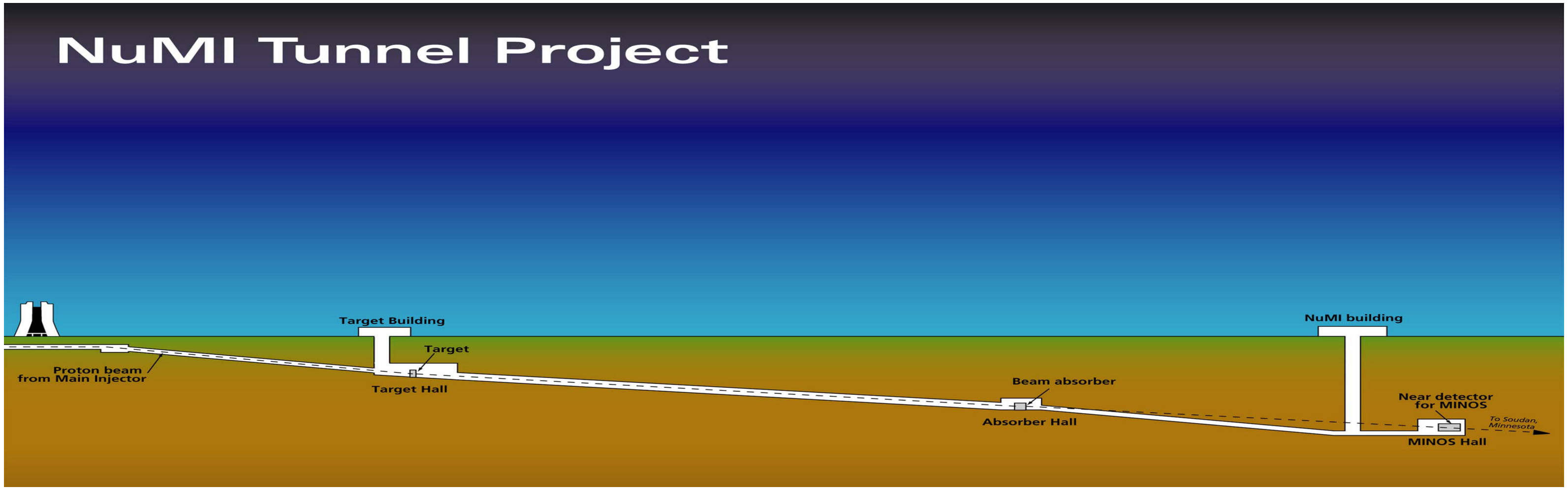
The MINOS Collaboration

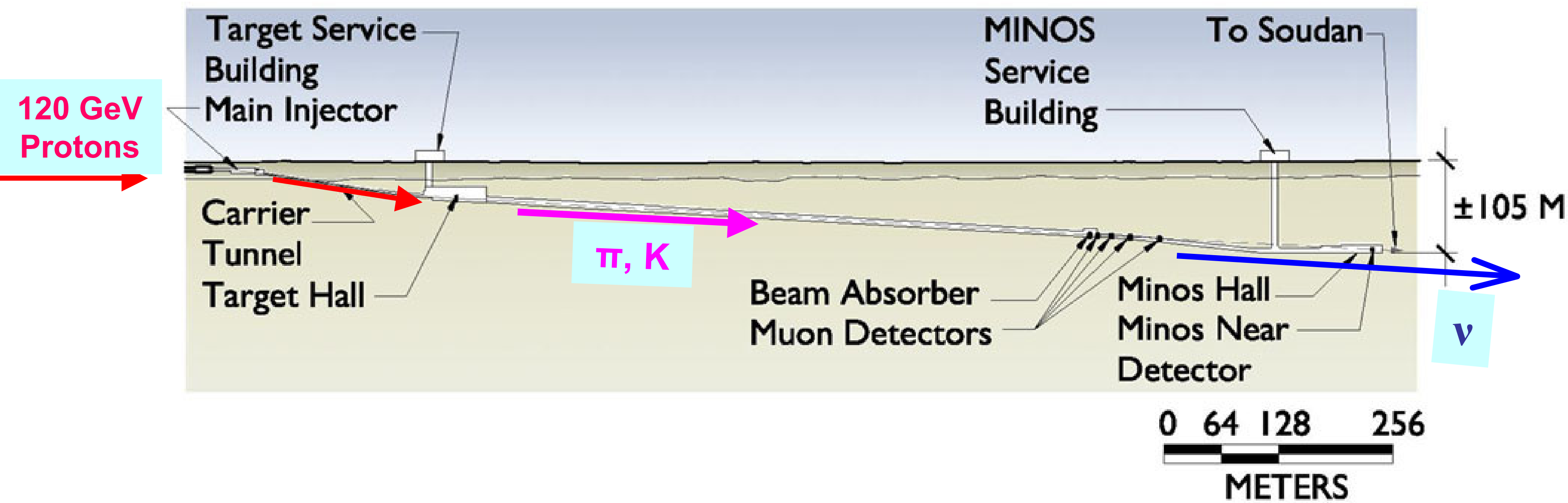
32 institutions
175 physicists

Brazil • France • Greece
Russia • UK • USA

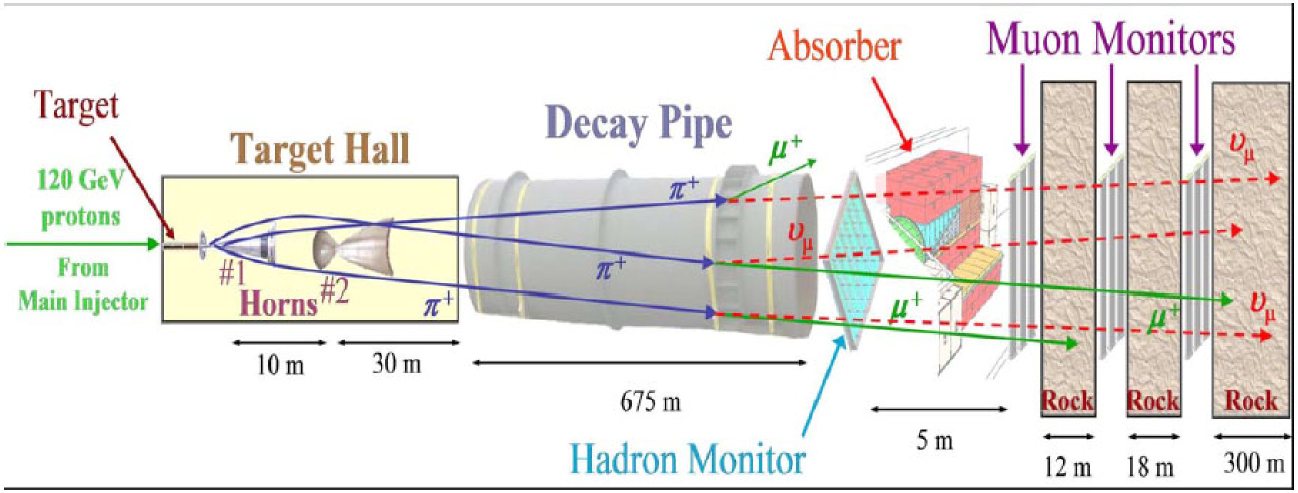
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Western Washington • William & Mary • Wisconsin

The NuMI Beam

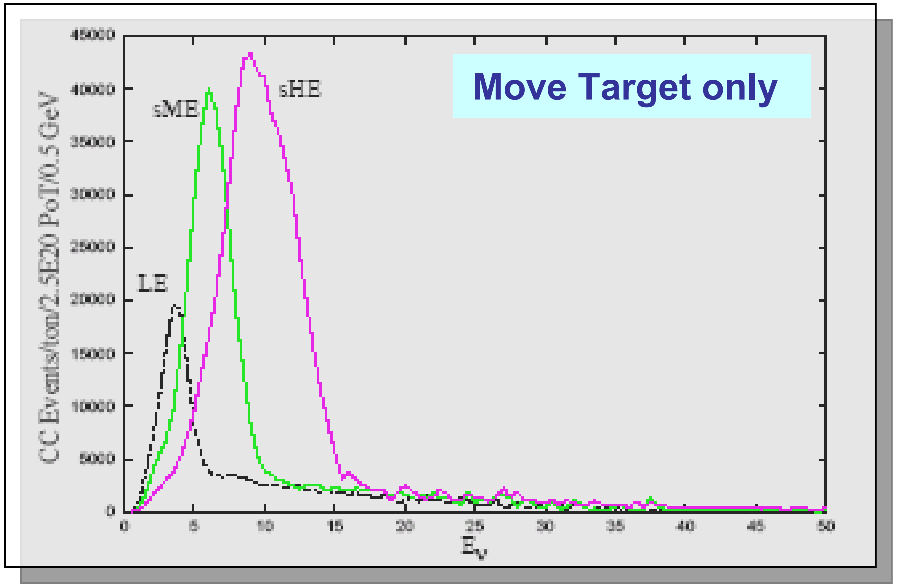


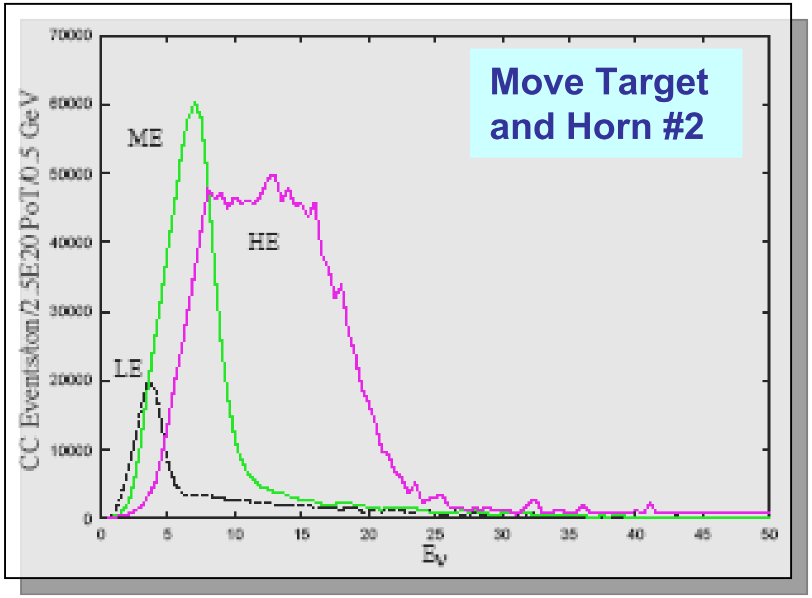


Neutrino Horns and Spectra



- 120 GeV primary Main Injector beam
- 675 meter decay pipe for pion decay
- Target readily movable in beam direction
- 2-horn beam adjusts for variable energy range

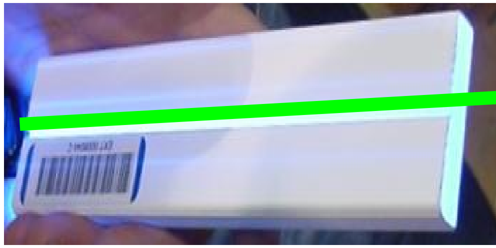




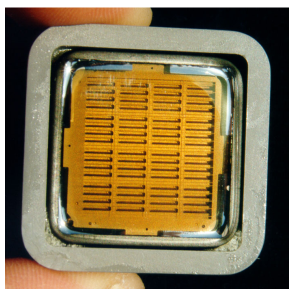
MINOS Detector Technology

WLS Fiber

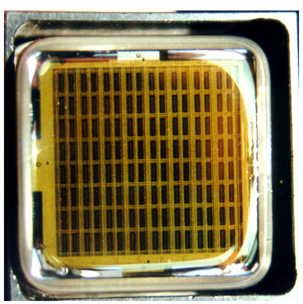
Scint Strip

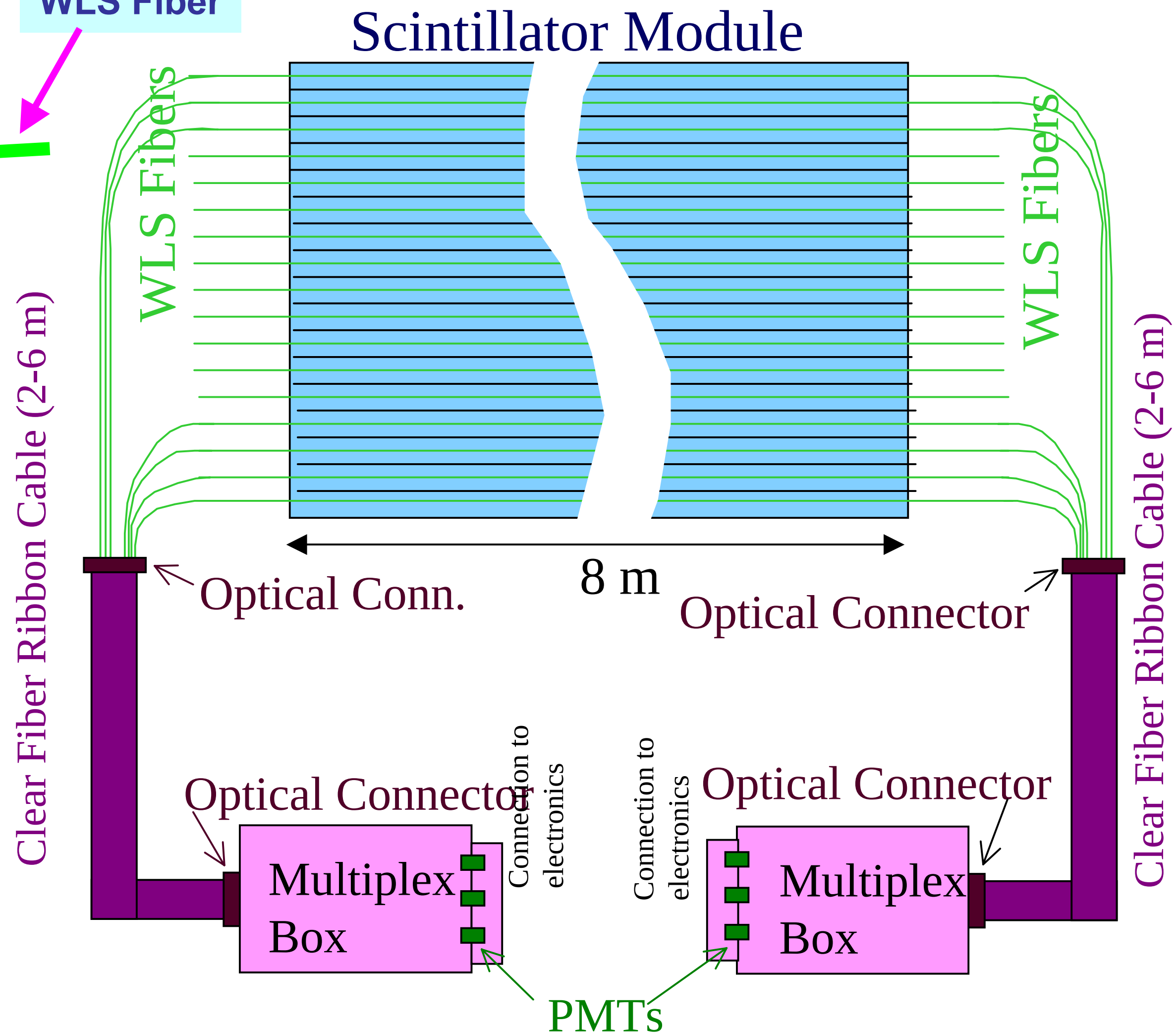


Far Detector: Hamamatsu M16 MAPMT



Near Detector: Hamamatsu M64 MAPMT





Objects not to scale

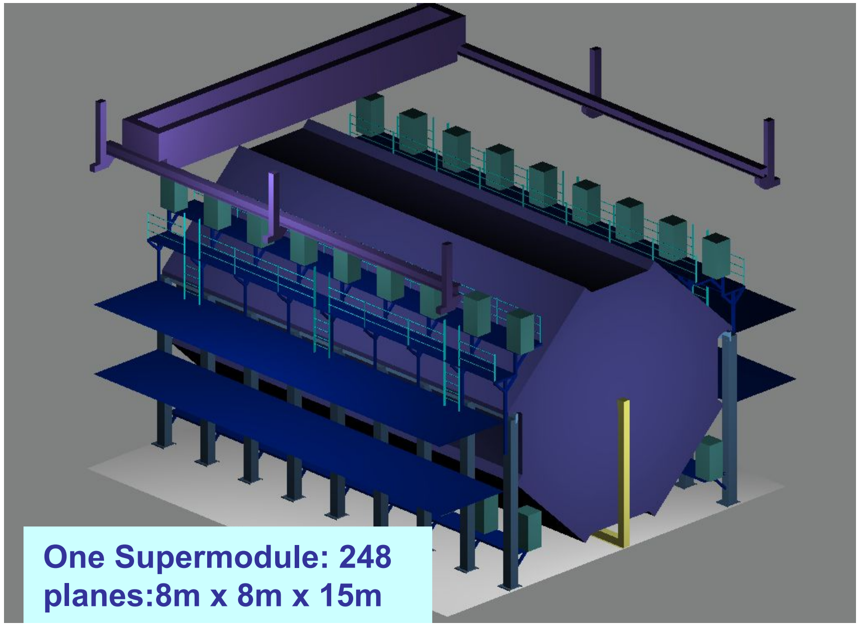
MINOS Far Detector

5.4 kton Magnetized Scintillator Calorimeter/Muon Spectrometer

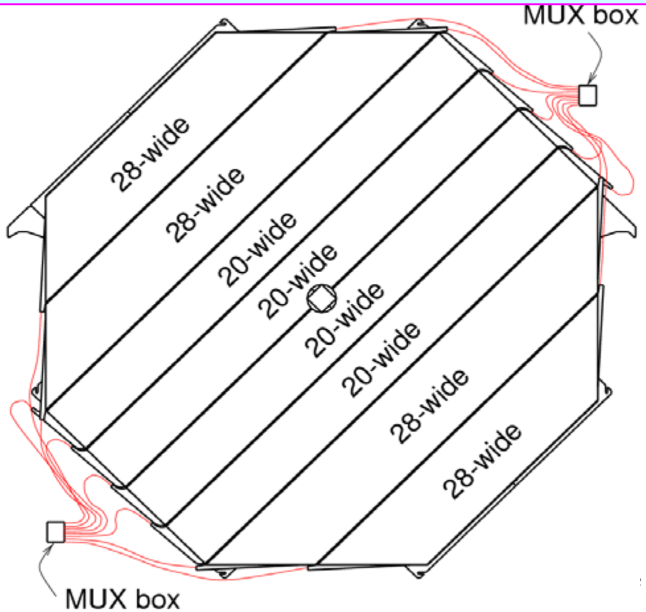
Structure: Steel / Scintillator

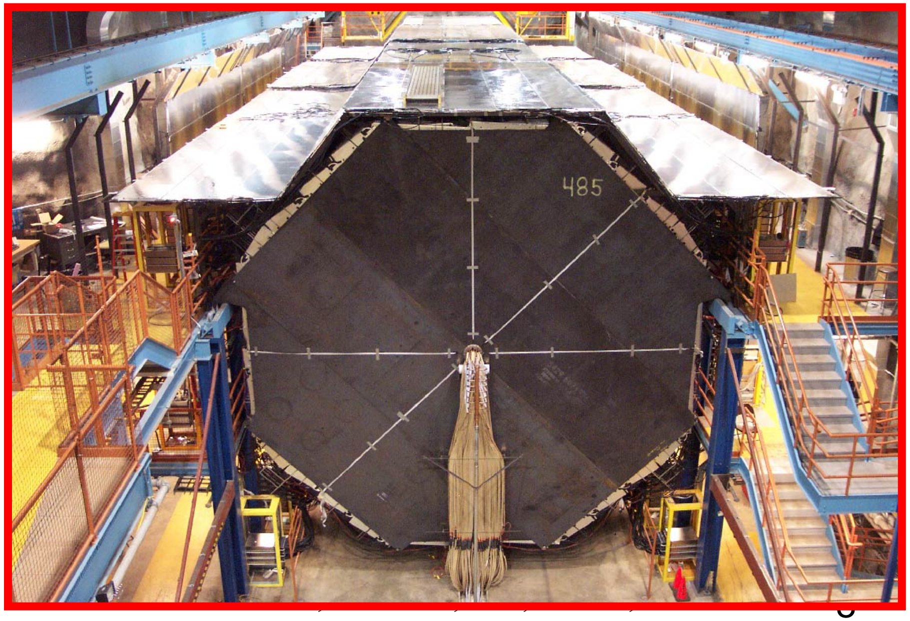
- 2.5 cm thick steel
- 4 cm x 1 cm polystyrene strips in Al cover
- WLS fiber
- 8m x 8m Octagonal Planes
- 8 modules/plane, 192 strips/plane
- 15.2 k A-turn coil
- Cosmic Ray Shield

Total: 486 Layers → 5.4 kTon



One Supermodule: 248 planes:8m x 8m x 15m



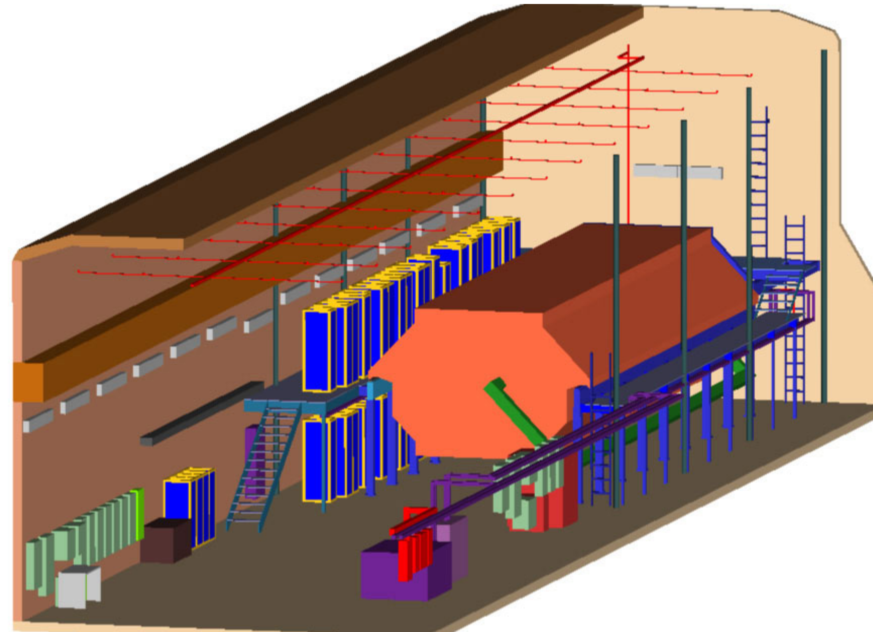


MINOS Near Detector

Emulates the Far detector in absorber, active planes, Bfield

Structure:

- veto
- Target section
- Shower detector
- muon spectrometer
- 282 steel planes
- 153 scint. Planes
- 1 kT, 3.8 m x 4.8 m "squeezed" octagon



George Tzanakos, University of Athens, Greece

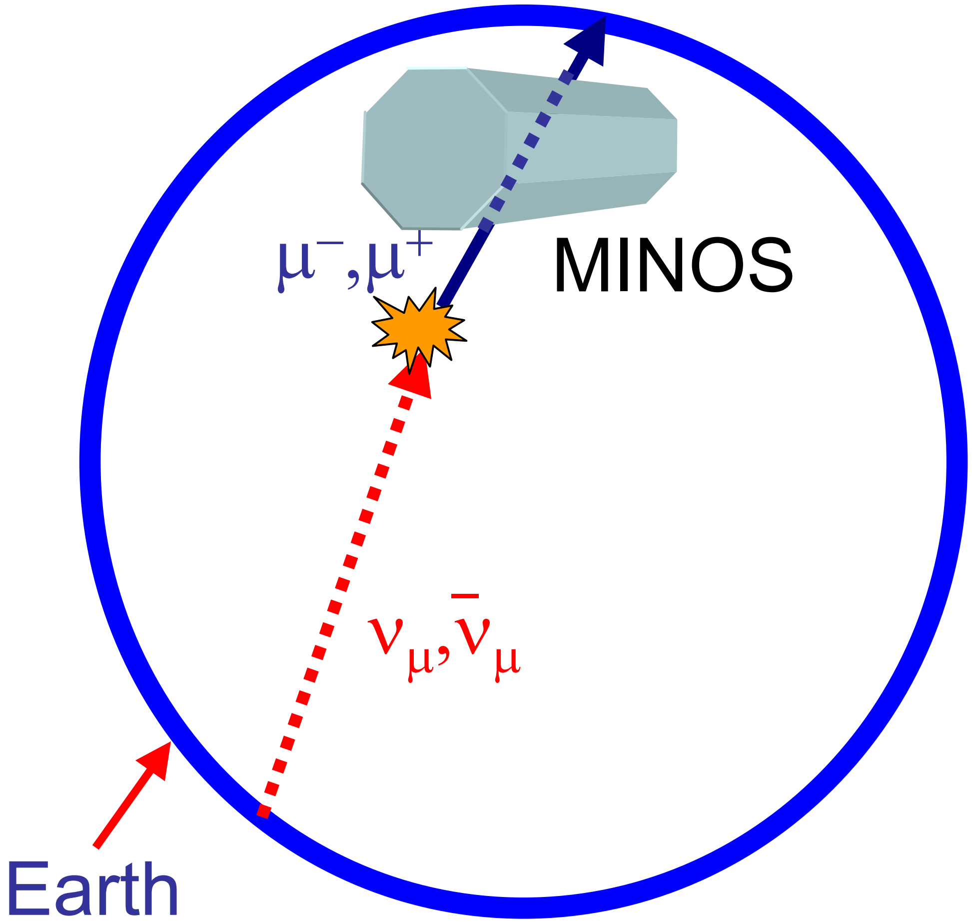
MINOS Detector Capabilities

1. Tracking
2. Muon detection:
   - Muon Charge sign
   - $\sigma^2_{1/p} = [0.13^2 + (0.3/p)^2]$ GeV^{-2} (p in GeV/c) (Curvature)
   - $(\sigma_p/p)^2 = [0.06^2 + (0.045/p)^2]$ (p in GeV/c) (Muon range)
3. EM shower detection: $\sigma_E/E \approx 0.23/E$, E in GeV
4. Hadronic shower: $\sigma_E/E \approx 0.55/E$, E in GeV
5. Timing: $\sigma \approx 2.3$ ns/ single hit
6. Veto shield rejection of cosmic rays

Measurement of:

- (1,2,3,4) $\rightarrow$ Neutrino event ID, E_ν Measurement
- (1,5) $\rightarrow$ particle direction
- (1,2,5) $\rightarrow$ up/down neutrino/antineutrino

Neutrino Induced Up-going Muons



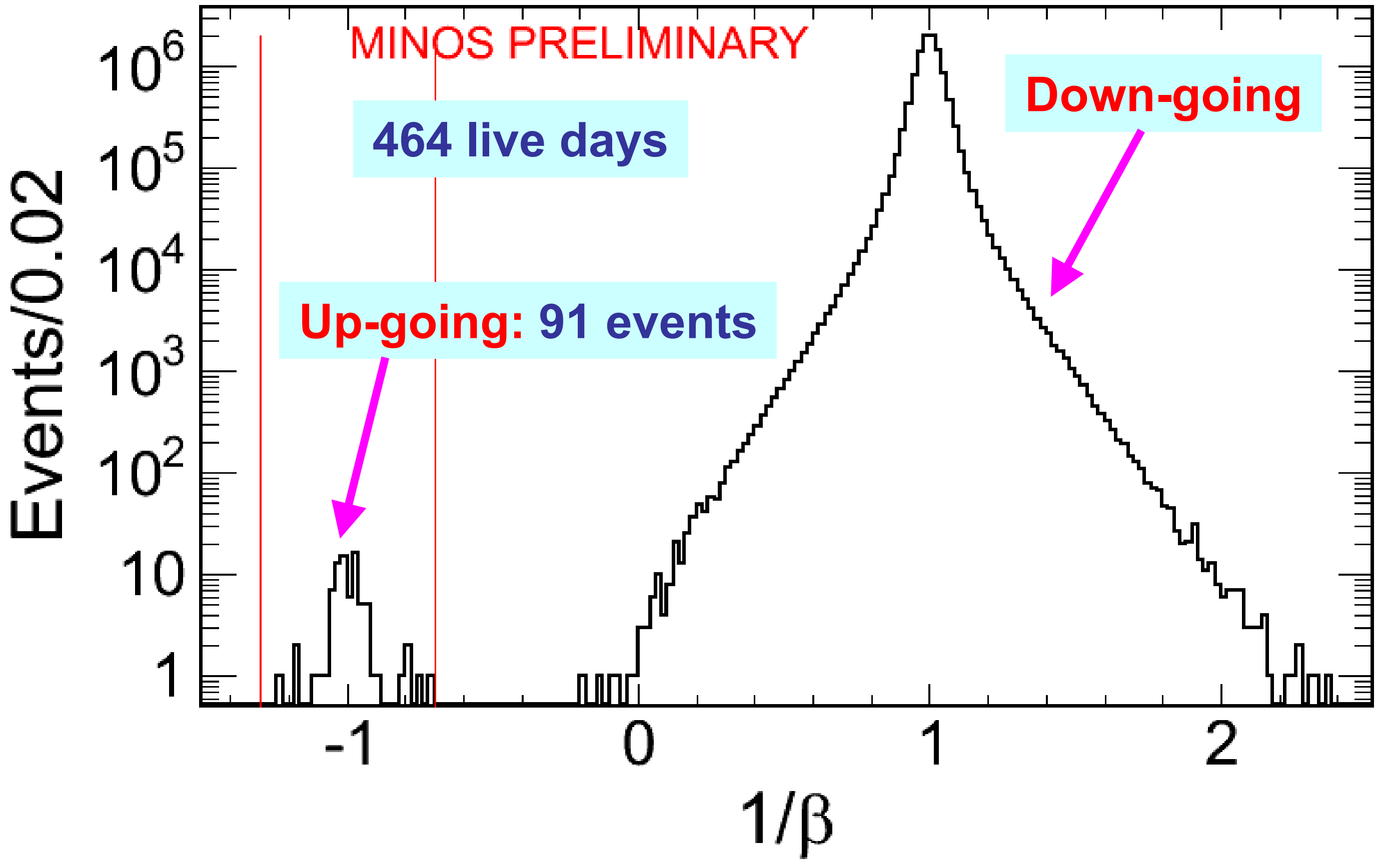
Data Collection: 464 live days

- 7/03 – 6/04 Normal BField
- 2/05 – 4/05 Normal BField
  - **304 live days**
- 6/04 – 1/05 Reverse BField
  - **160 live days**

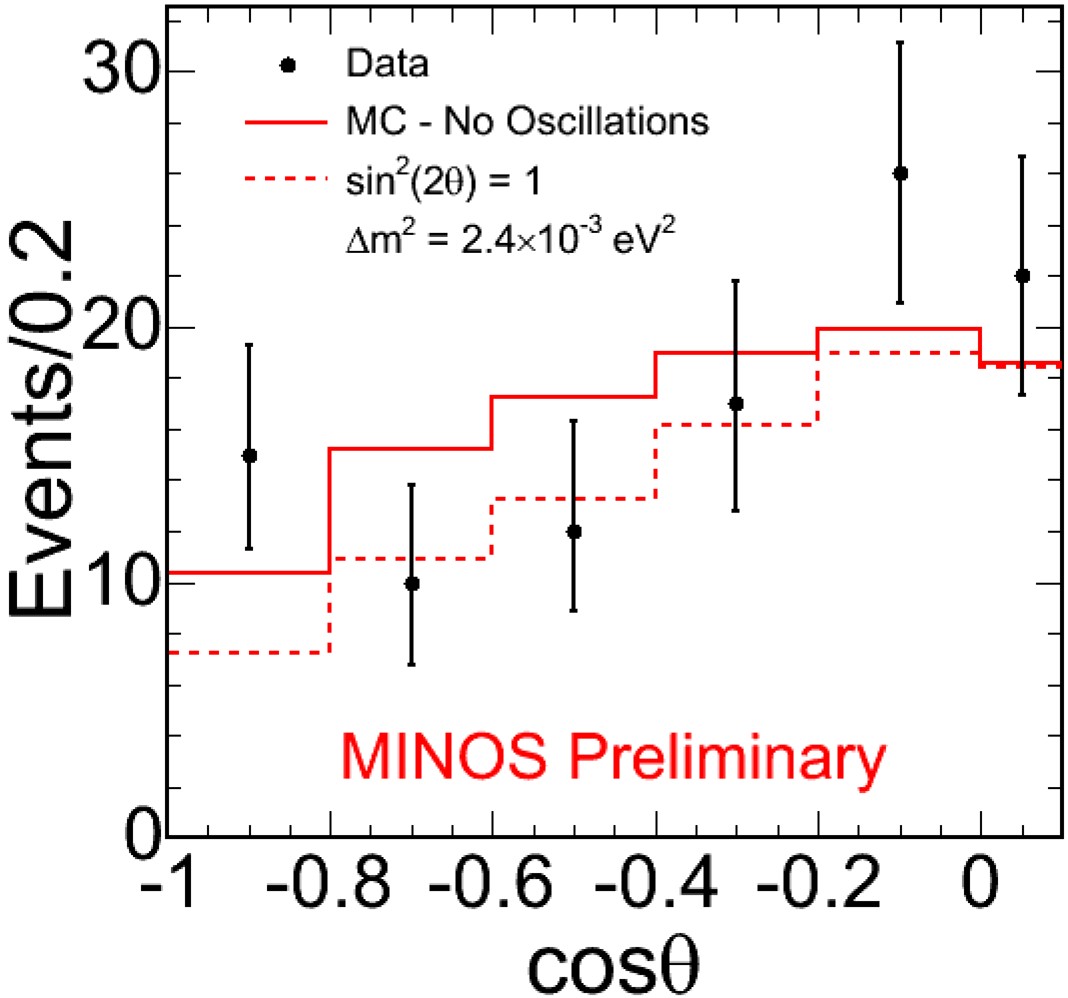
Data Analysis

- **Muon ID cut**
- **Track quality**
- **Fiducial (Muon enters detector)**
- **Direction consistent with timing and tracking**
- **1/β cut, ($\beta c = v = ds/dt$)**

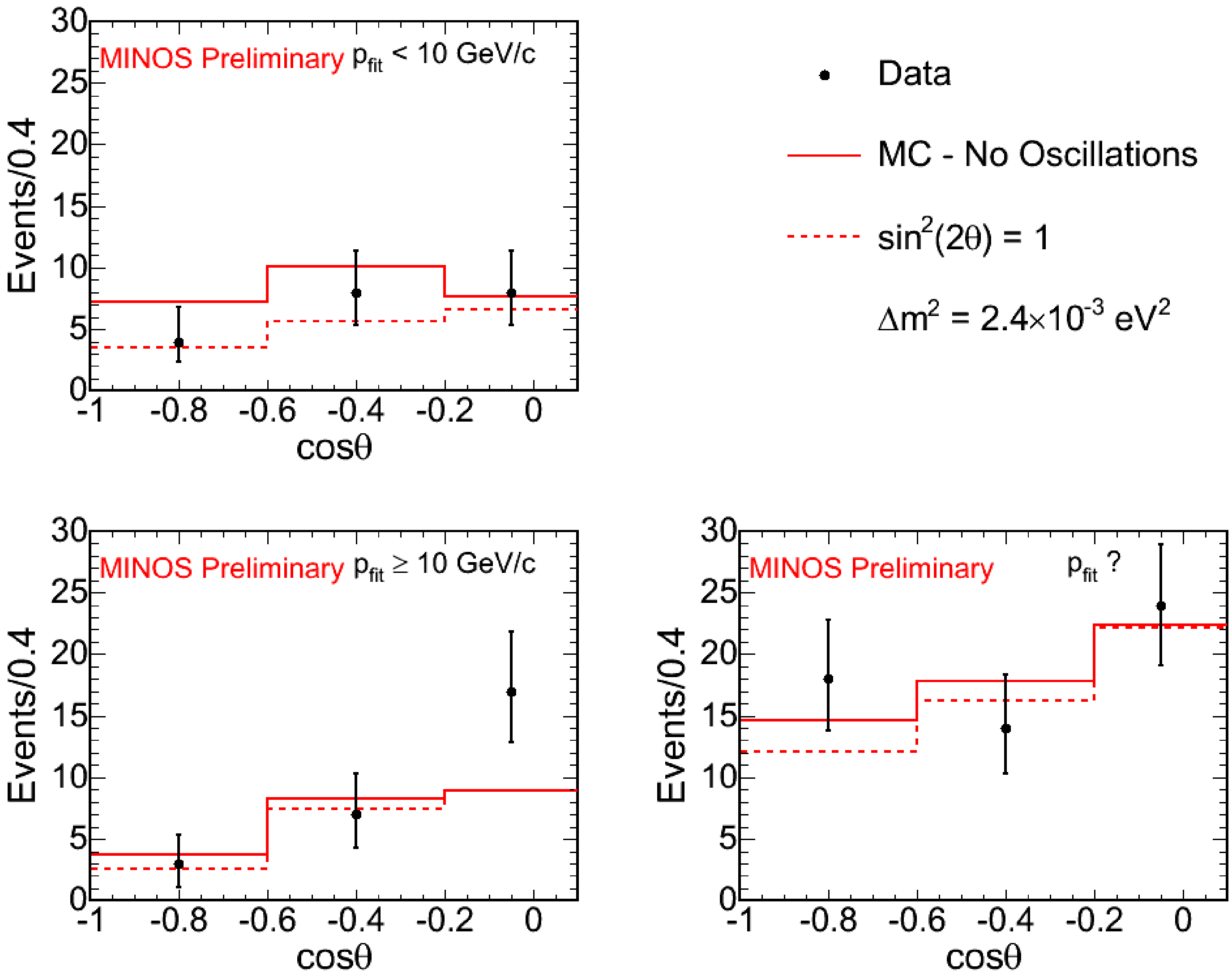
Up-going muons: 1/beta distribution



Up-going muons: Zenith Angle



Zenith Angle Distribution vs Momentum



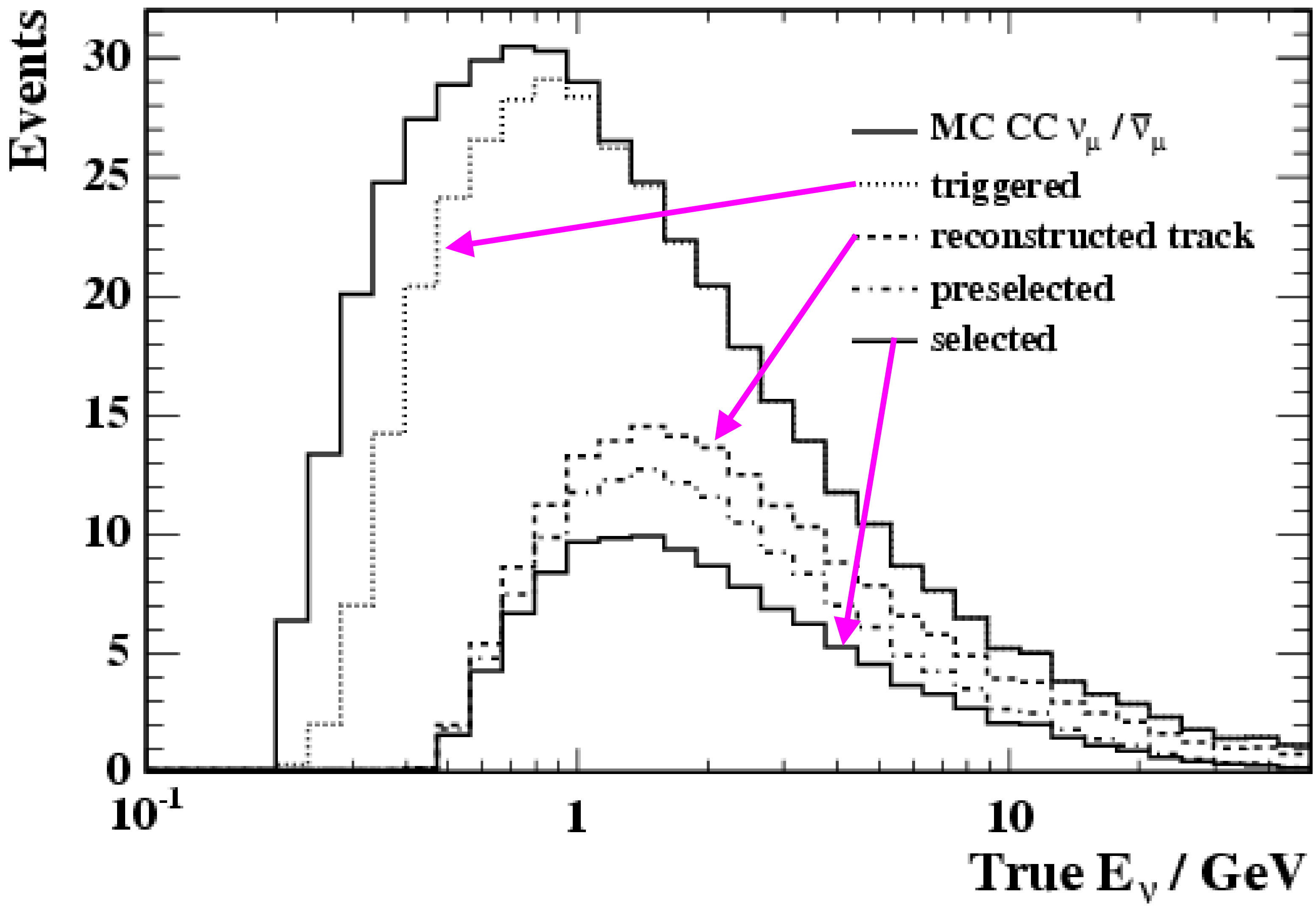
FC and PC Atmospheric Neutrinos

- 418 Live days of data in the MINOS Far Detector $\rightarrow$ Exposure of 6.18 Kt-years (4.54 kt – years fiducial).
- Up/down neutrino/antineutrino ID from Magnetic Field + tracking + timing
- S/B 10:1 requires a 10^6 background rejection
- Event selection cuts identify Fully-Contained (FC) and Partially-Contained (PC) ν_μ/ $\bar{\nu}_\mu$ events.

Event Selection

- Preselection cuts: Mainly containment
- Selection of FC and downward PC (Dominant BGND: Steep Cosmic Rays: Large charge depositon in a sigle plane near the track beginning)
  - Cosmic Ray rejection: (Δ_z < 0.5 m $\rightarrow$ reject track)
  - Event Topology cut (remaining S/B = 1:5)
  - Vertex charge/direction cut (remaining S/B = 1:1)
  - Veto Shield cut (timing: $\pm$ 100ns around event time)
- Selection of Upward PC Events
  - Event Topology
  - Track timing

Atmospheric FC + PC: Results



Atmospheric FC + PC: Results

Selection	Data	Expected No Oscillations	Expected Δm^2_{23}=0.0024 eV^2
Good timing	77	90 ± 9	68 ± 7
Low Resolution (Uncertain direction)	30	37 ± 4	28 ± 3
All Events	**107**	**127 ± 13**	**96 ± 10**

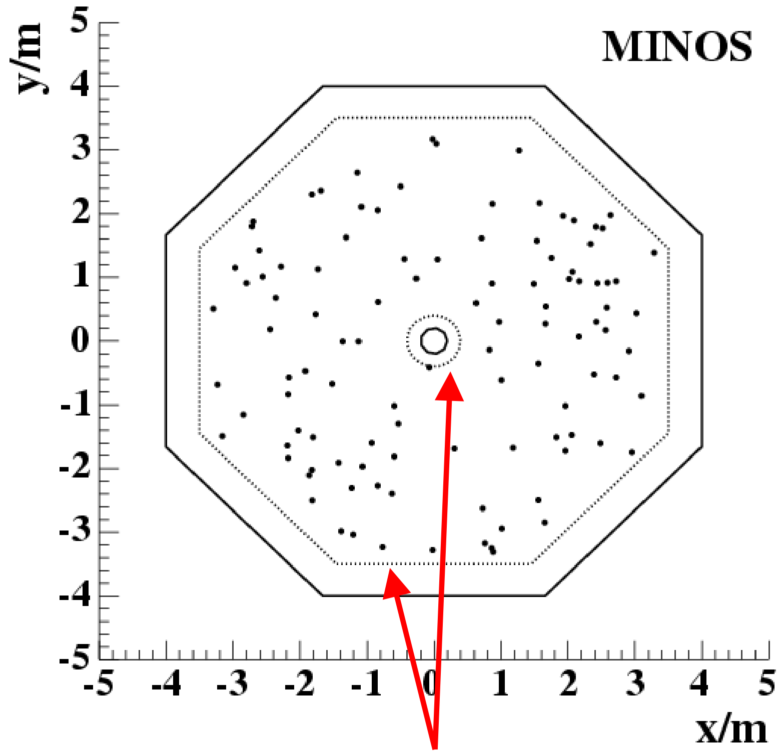
Breakdown

FC	69
PC Down	25
PC up	13
Total	**107**

Background

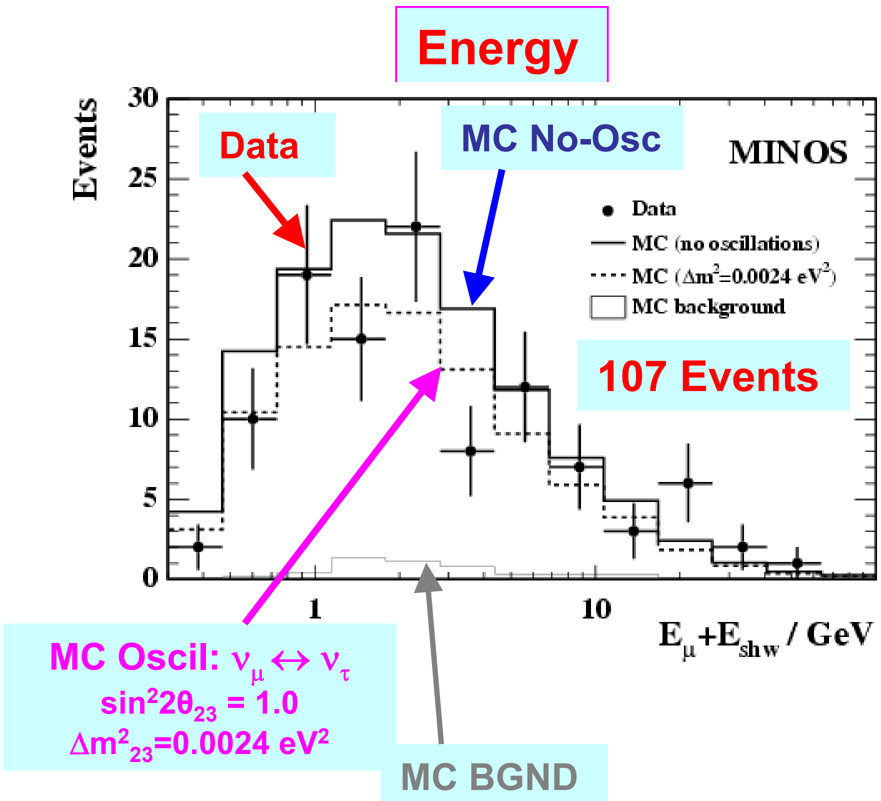
CR Muons (from data)	4.4±0.5
NC + ν_e/ $\bar{\nu}_e$ CC (Estimated)	4.5±0.5

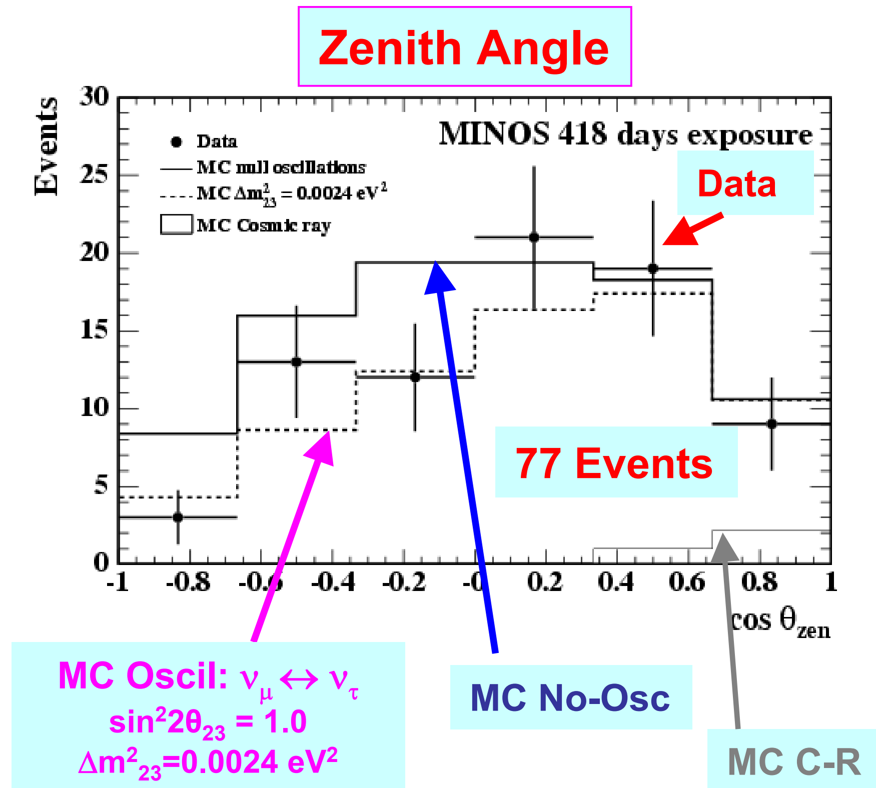
Vertex x-y plot



Fiducial Cuts

Atmos FC + PC: Energy and Zenith Angle





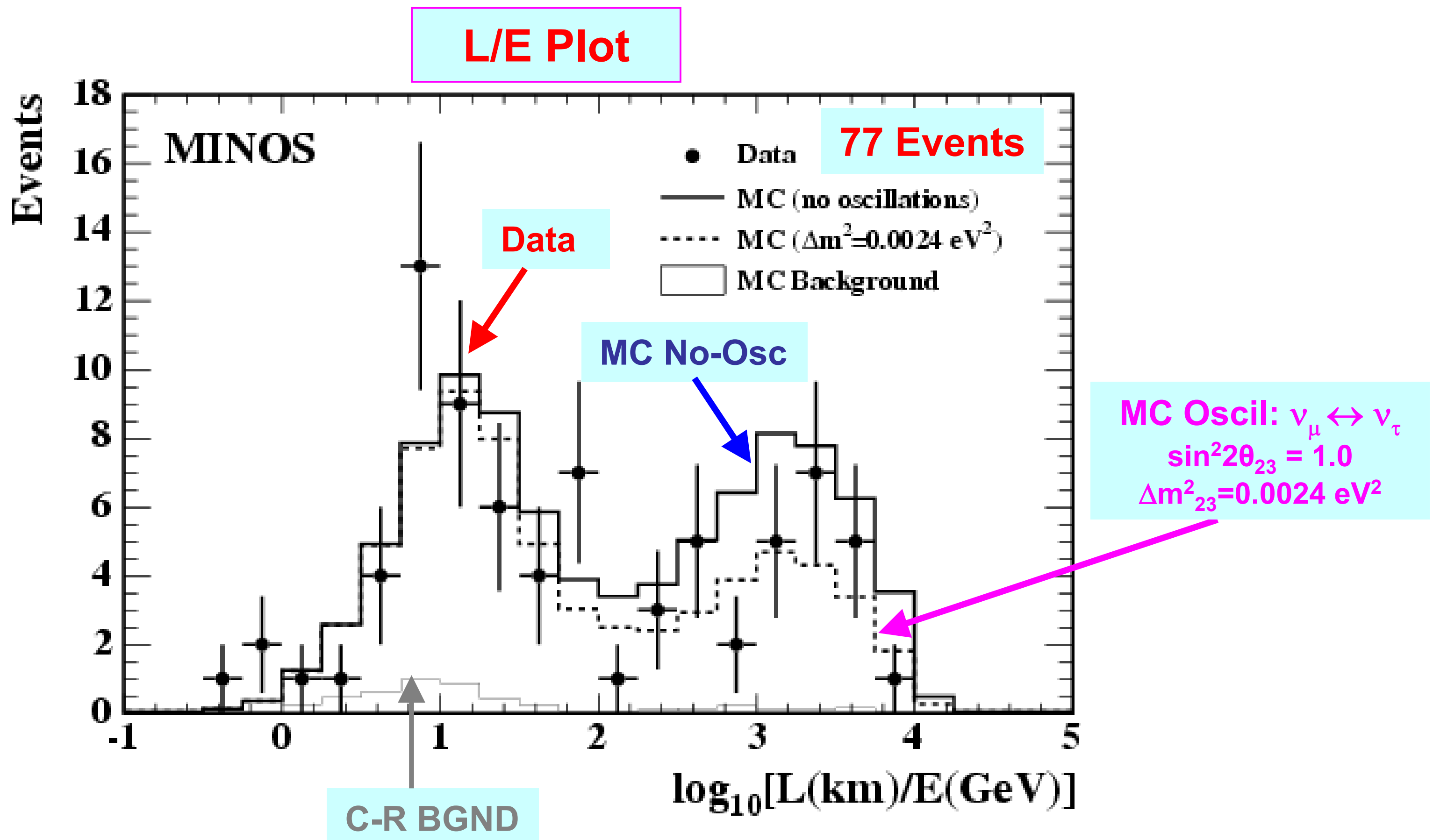
Upward-going/Downward-going Double Ratio

$$R^{data}_{up/down} / R^{mc}_{up/down} = 0.62 \pm 0.14(stat.) \pm 0.02(syst.)$$

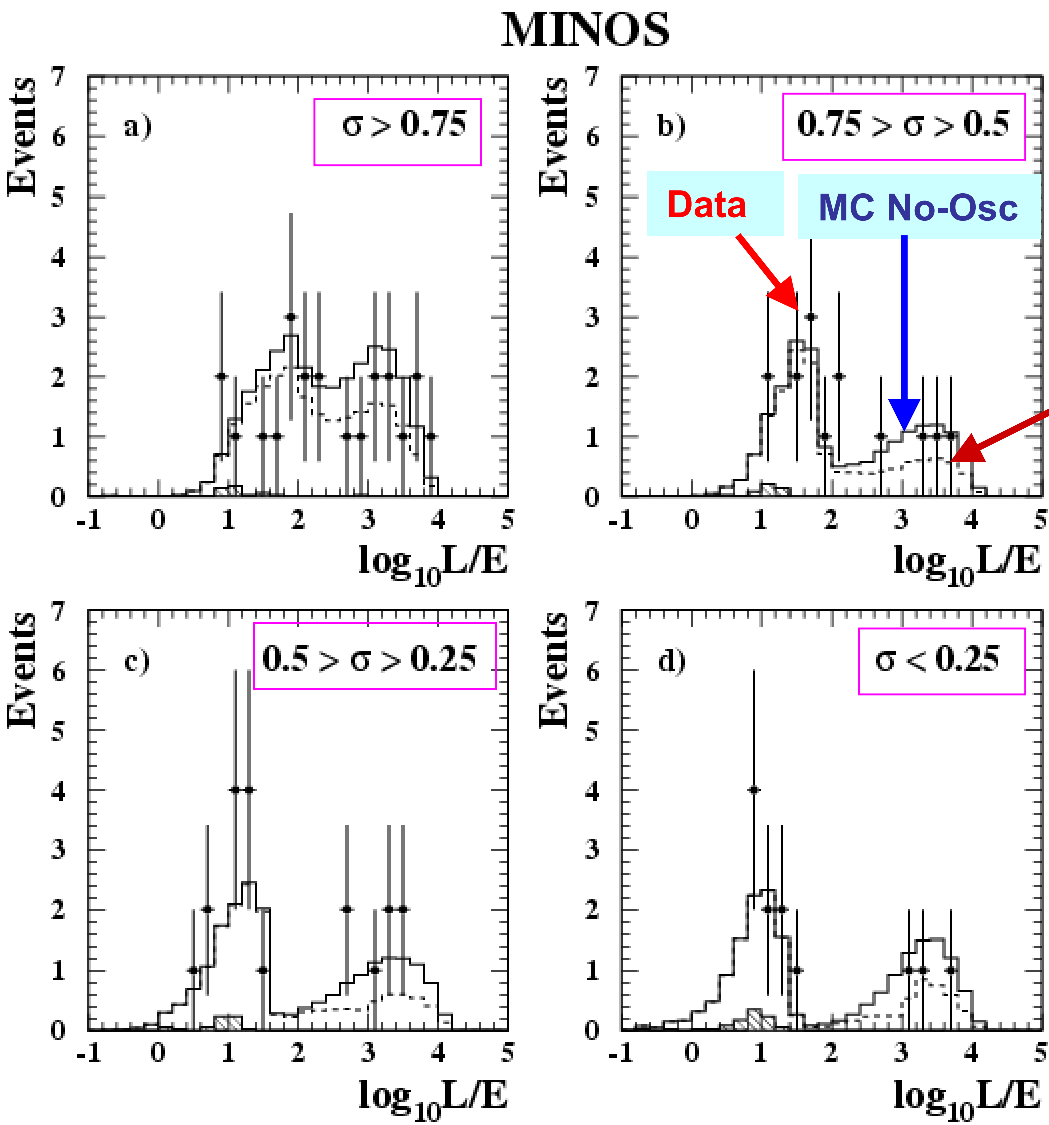
Atmos FC + PC: Oscillation Analysis

Oscillation Probability: $P\left(\nu_\mu \rightarrow \nu_\mu\right) = 1.0 - \sin^2 2\theta_{23} \sin^2\left(1.27 \Delta m^2_{23} \frac{L}{E}\right),$

$where: \Delta m^2_{23}[eV^2],\ L[km],\ E[GeV]$



ATMOS L/E vs. rms



Maximum Likelihood Fit:

$\nu_\mu \leftrightarrow \nu_\tau$

$\sin^2 2\theta_{23} = 0.90$

$\Delta m^2_{23} = 0.0013\ eV^2$

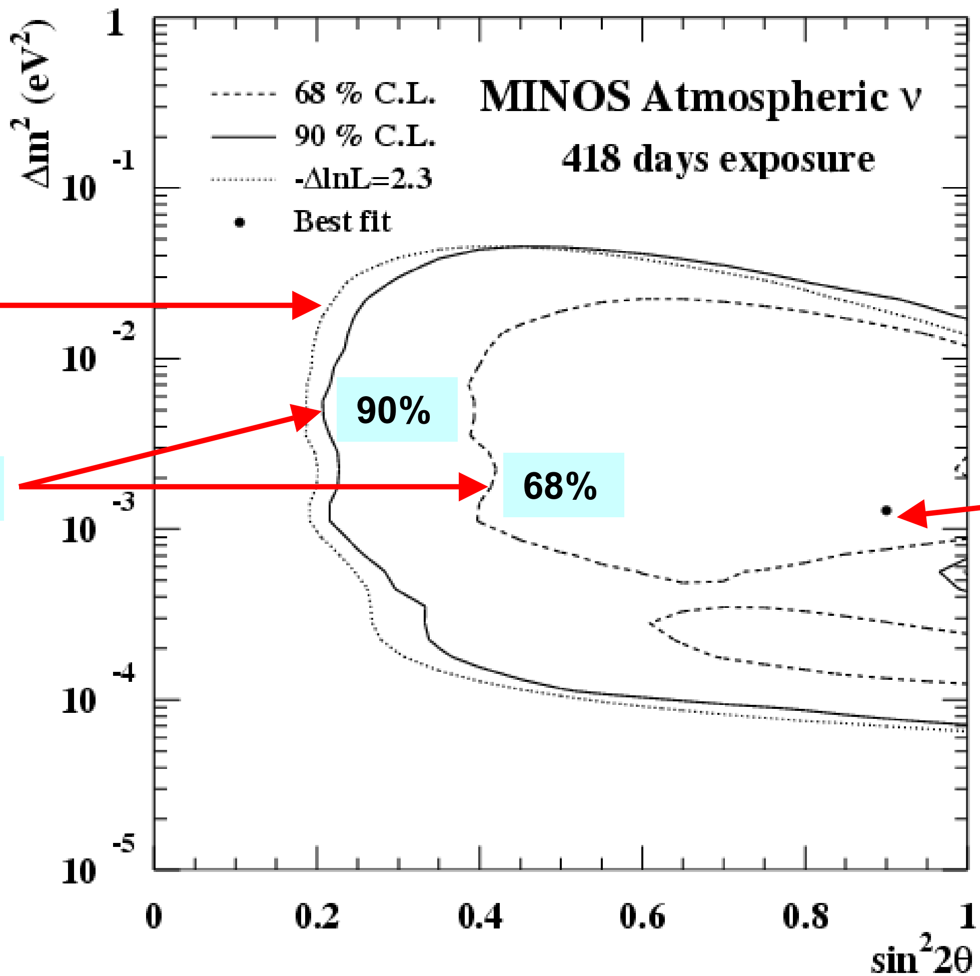
(best fit)

MINOS ATMOS: Oscil Limits

-ΔlnL = 2.3

90% CL

Feldman - Cousins



Best Fit

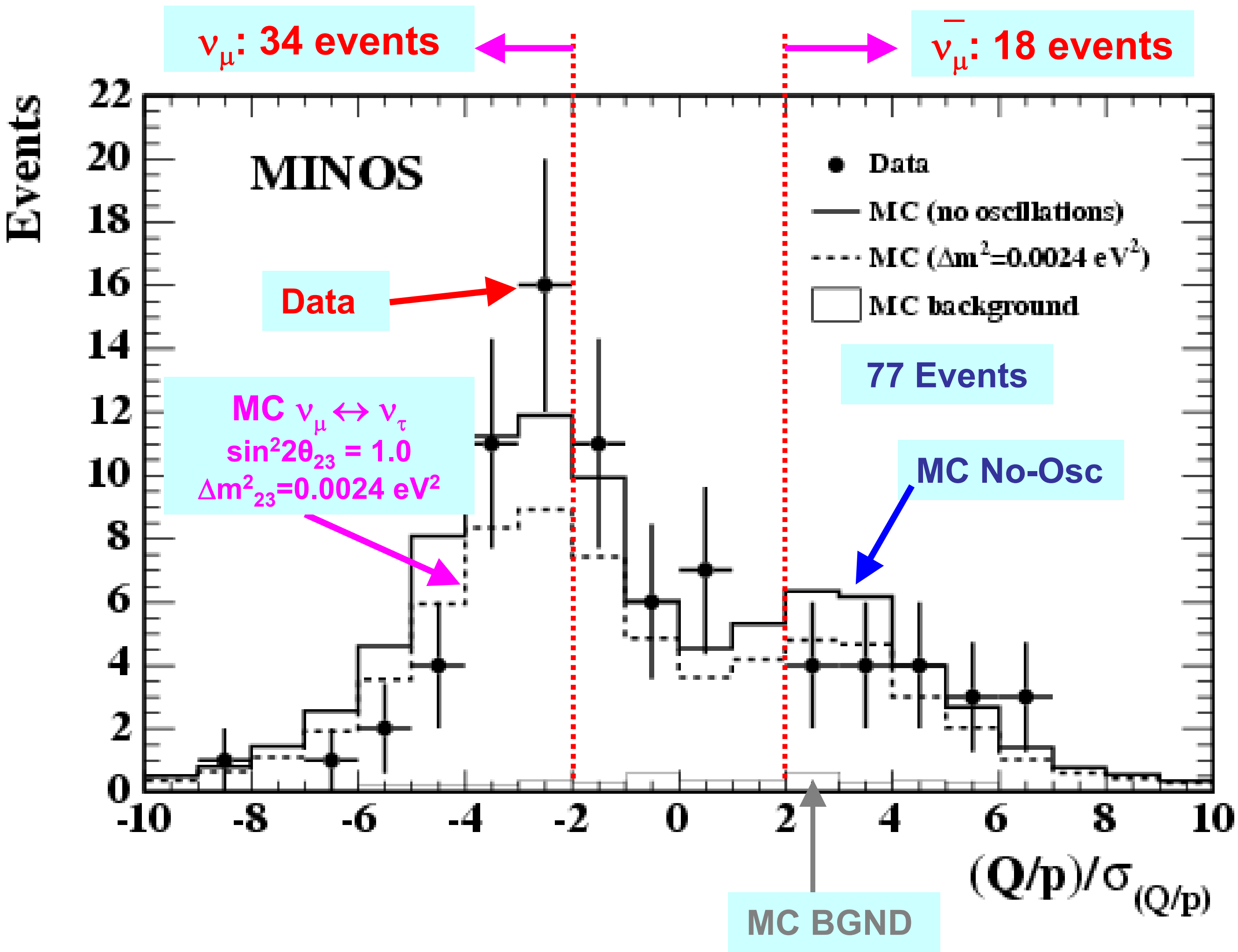
$\nu_\mu \leftrightarrow \nu_\tau$

$\sin^2 2\theta_{23} = 0.90$

$\Delta m^2_{23} = 0.0013$ eV^2

MINOS ATMOS: Charge Ratio

ν_μ versus $\bar{\nu}_\mu$



ATMOS: Charge Separated Up/down Distributions

Selection	Data	Expected No Oscilations	Expected $\Delta m^2_{23}=0.0024\ eV^2$
Low Resolution	30	37 ± 4	28 ± 3
Ambig $\nu_\mu / \bar{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\bar{\nu}_\mu$	18	23 ± 2	17 ± 2

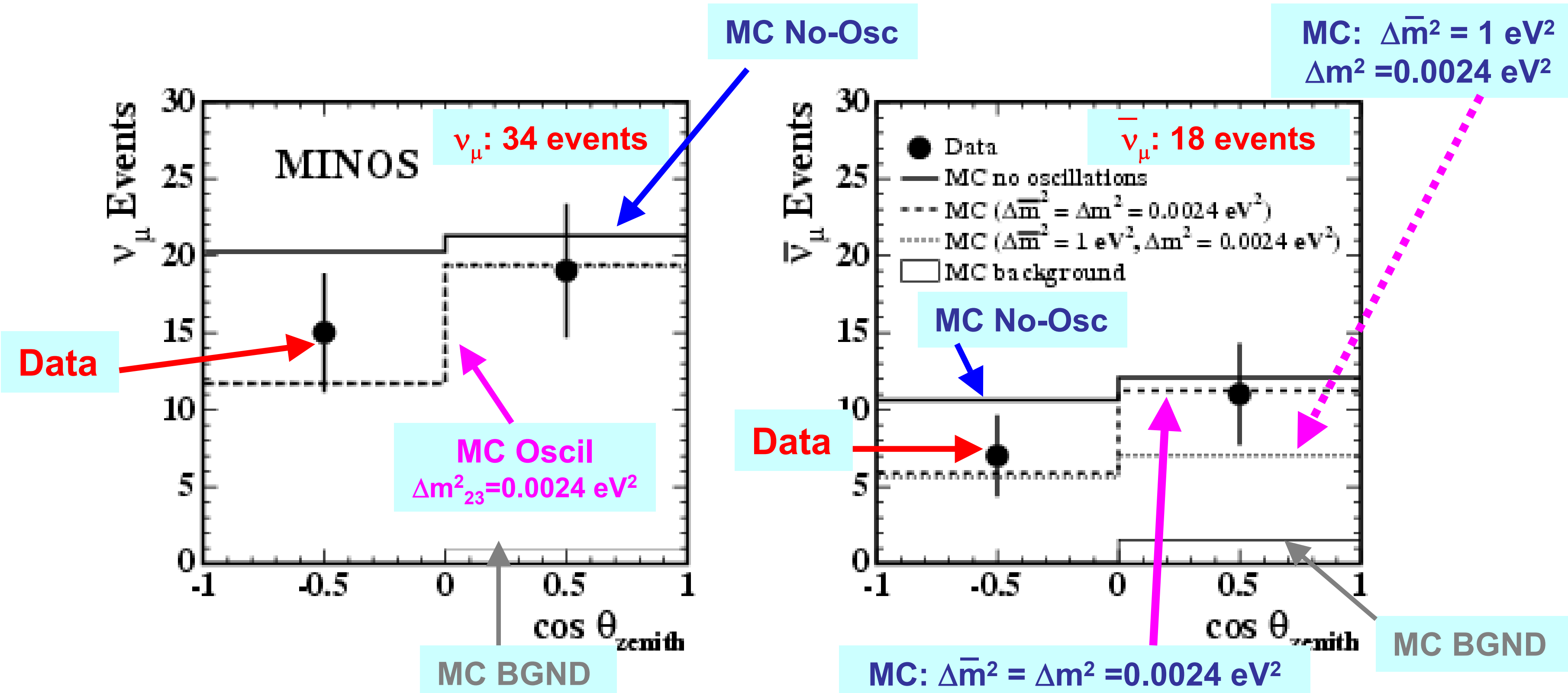
$$f_{data} = \frac{N(\bar{\nu}_\mu)}{N(\nu_\mu + \bar{\nu}_\mu)} = 0.35 \pm 0.07(stat.) \pm 0.02(syst.) \equiv \bar{\nu}_\mu \text{ fraction}$$

$\bar{\nu}_\mu$ fraction: Data vs MC

$$f_{data} / f_{MC} = 0.98 \pm 0.19(stat.) \pm 0.06(syst.)$$

MC assumption: ν_μ and $\bar{\nu}_\mu$ oscillate with same parameters

ATMOS: Charge Separated Up/down Distributions



- Data consistent with ν_μ and $\bar{\nu}_\mu$ oscillating with same parameters.
- CPT violating scenarios with large Δm^2_{23} not excluded with current data

MINOS: Accelerator Neutrinos

Detectors

• MINOS Far Detector completed in July 2003, Magfield in August 2003.

• MINOS Near Detector completed and commisioned by the end of 2004

NuMI Beam

• NuMI beam completed and commisioned by March 2005

• NuMI Beam has delivered: 6.7×10^{19} POT. Hope to have $\underline{1 \times 10^{20}}$ POT by the end of 2005

Data Collection

• MINOS Near Detector has accumulated high statistics

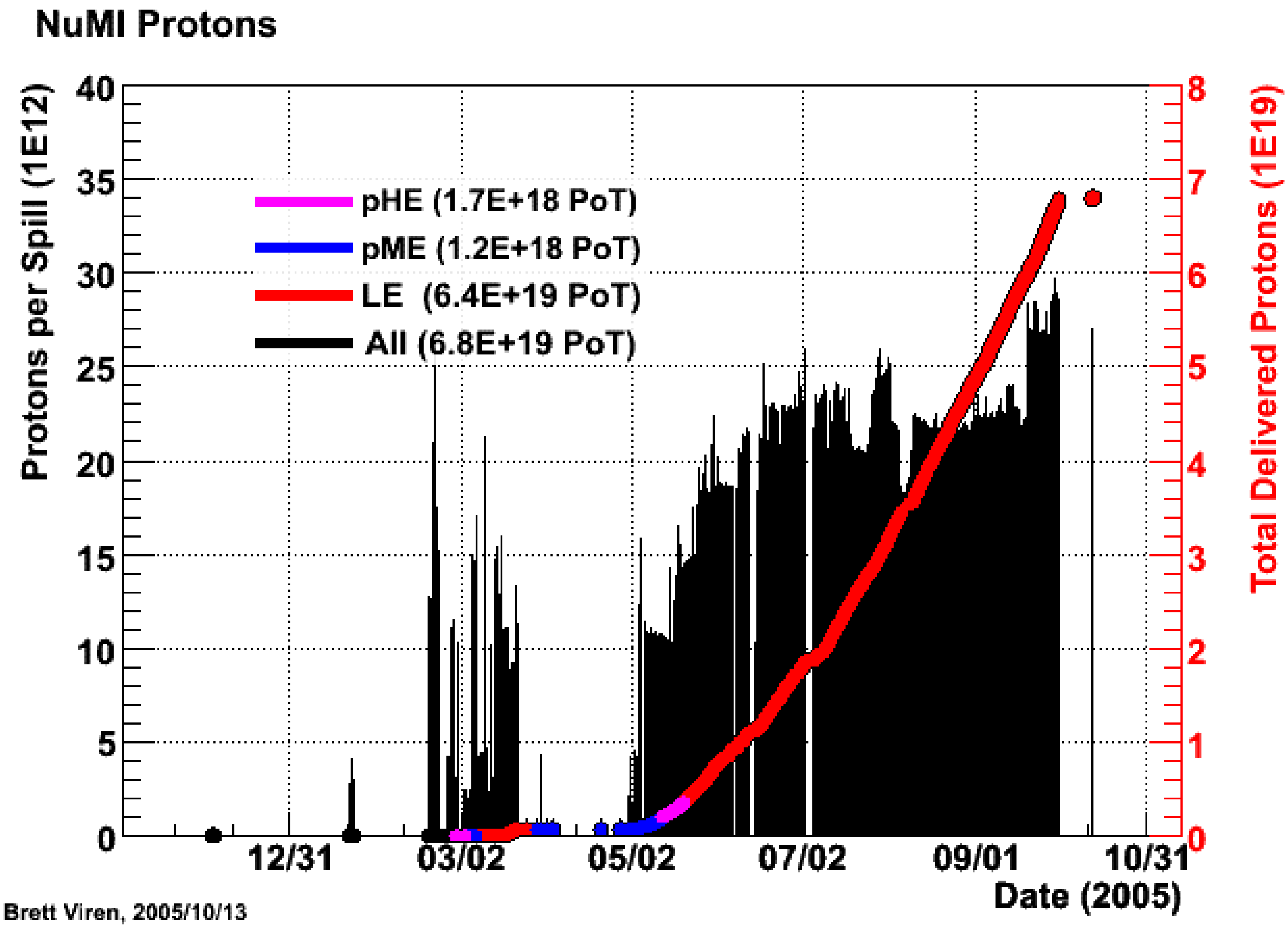
• MINOS Far Detector "sees" NuMI beam neutrino interactions

Data Analysis

• Physics Analysis tools in preparation

• Far Detector uses Blind Analysis.

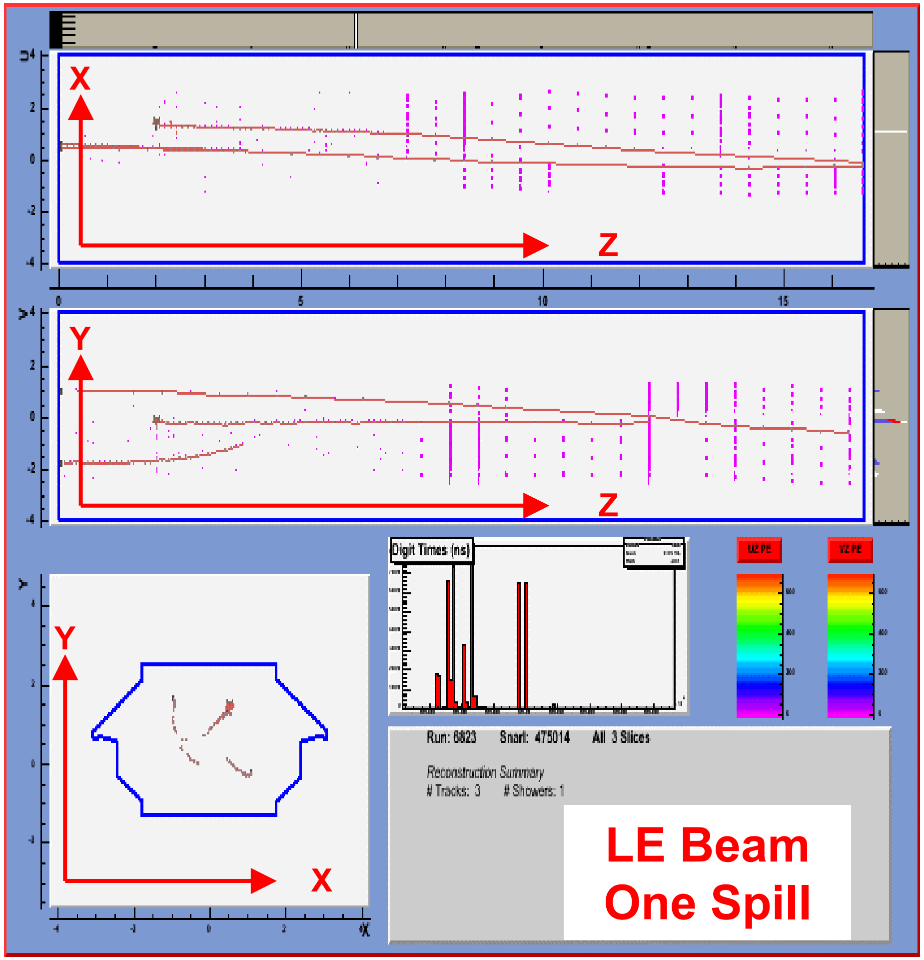
NuMI Beam: Protons on Target

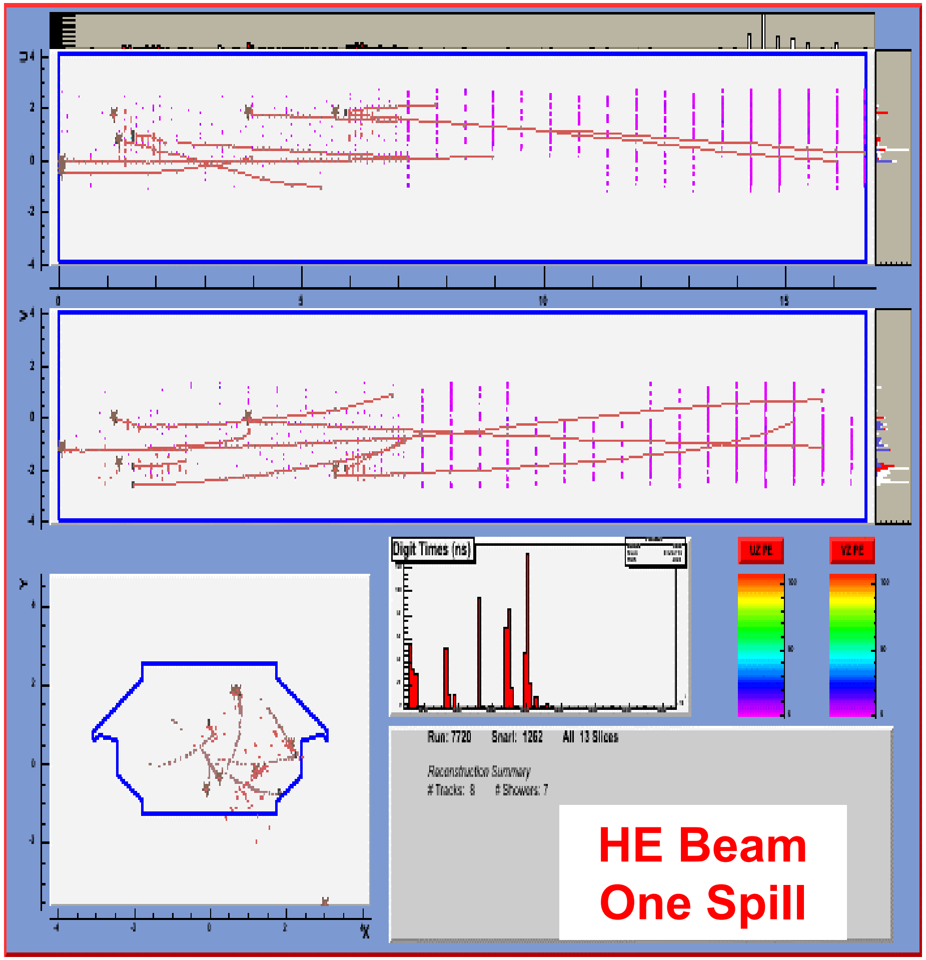


Beam Neutrinos: Near Detector

Activity within Spill: 8-10 μs , 5-6 buckets (~ 1.6 μs long)

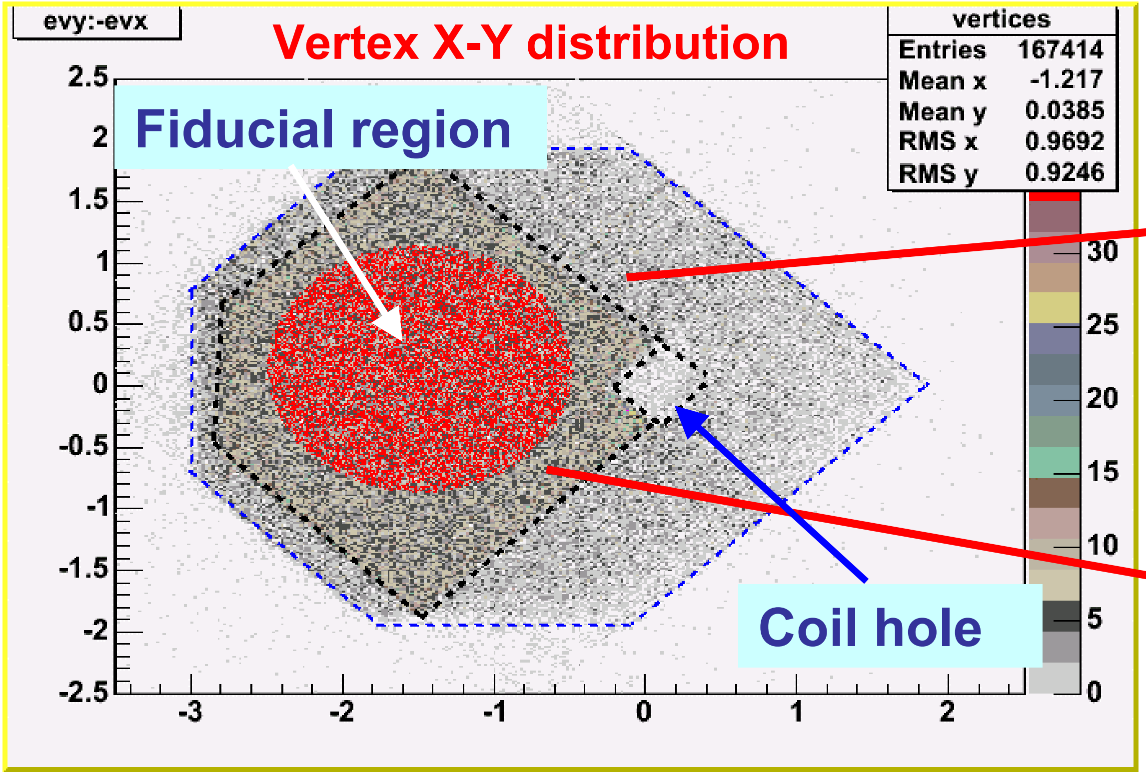
Several events: Separate by time slicing and topology : 18.9 ns resolution

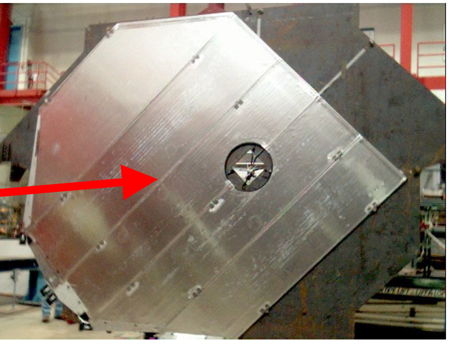


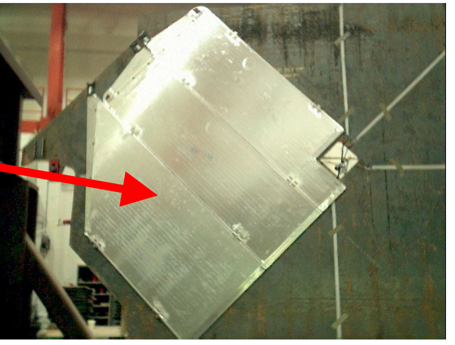


Beam Neutrinos: Near Detector

Multiple interactions per spill: High Statistics sample in the ND



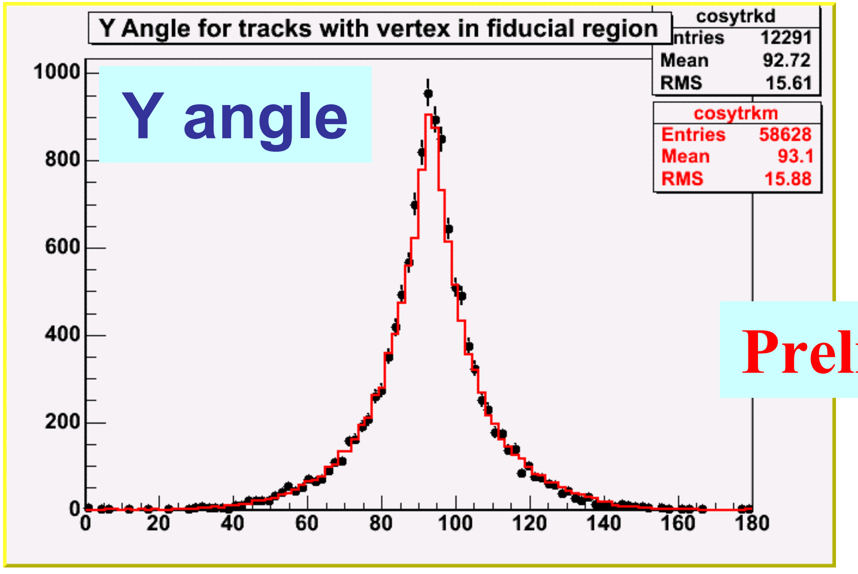




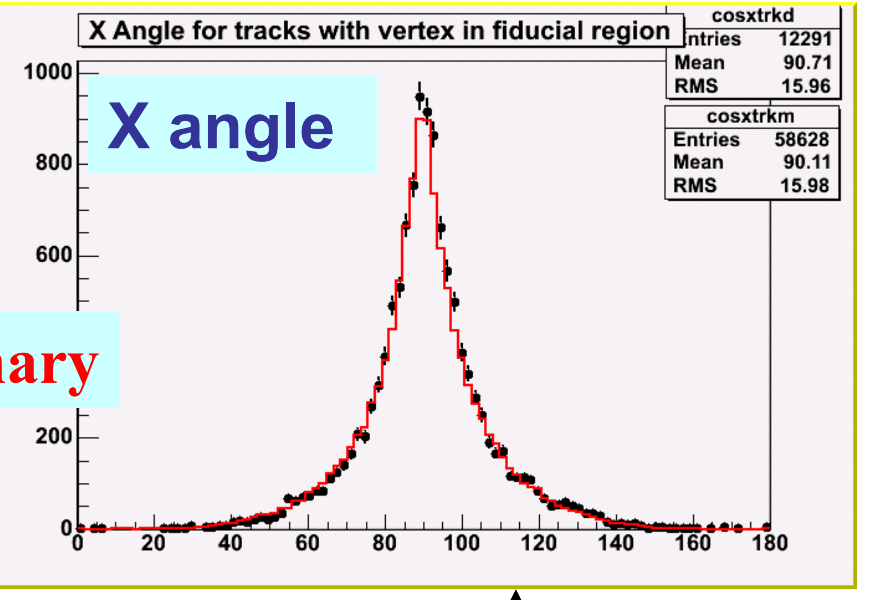
NuMI Beam: Pointing to the Far Detector

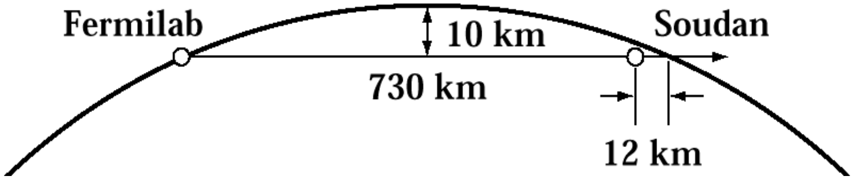
Y-angle must be 3 deg down, ie 93 deg.

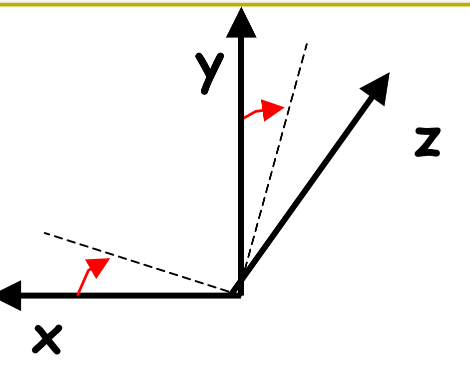
Shown below: Muon track direction



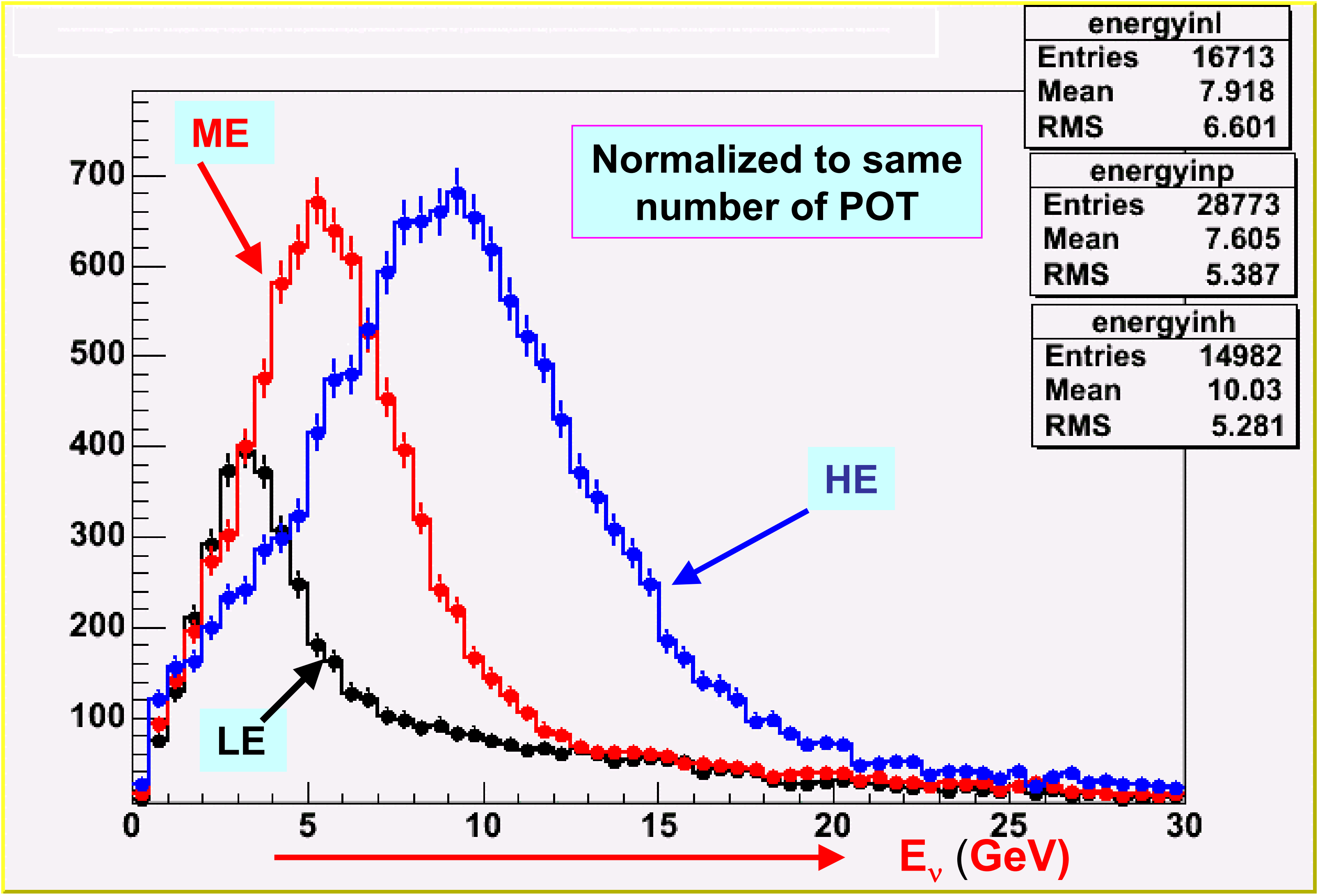
Preliminary



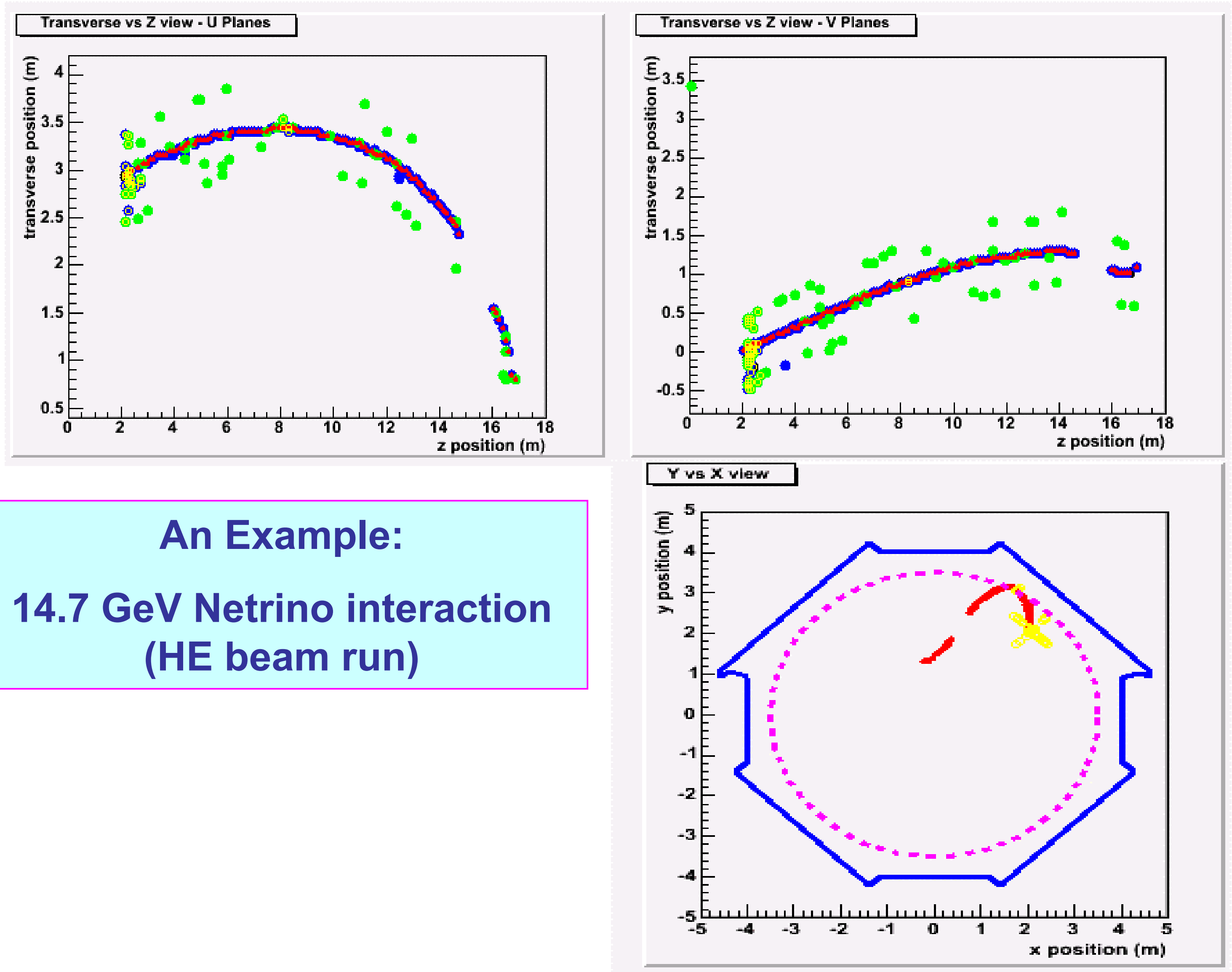




Near Detector Data: Energy Scan



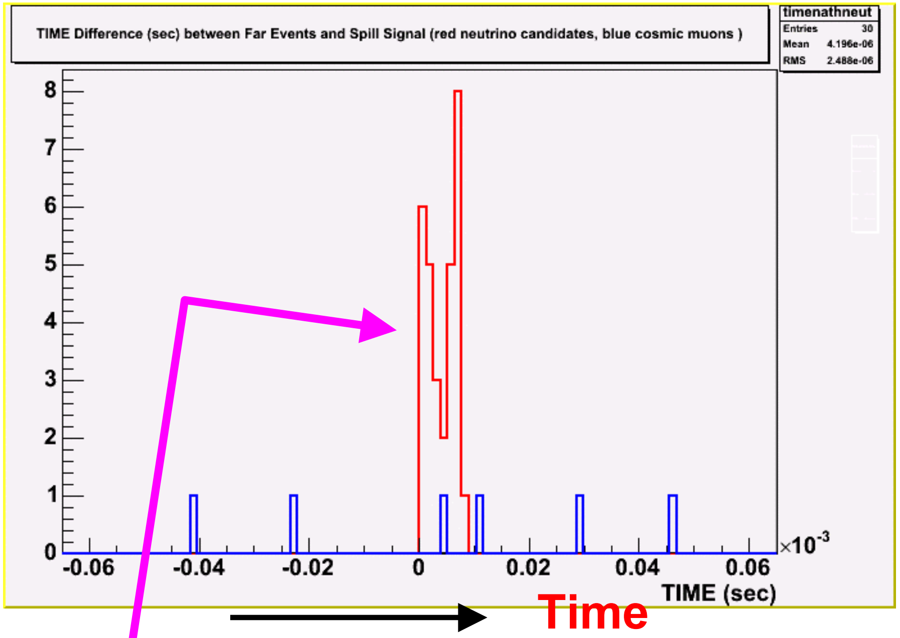
Far Detector: Numu CC Event

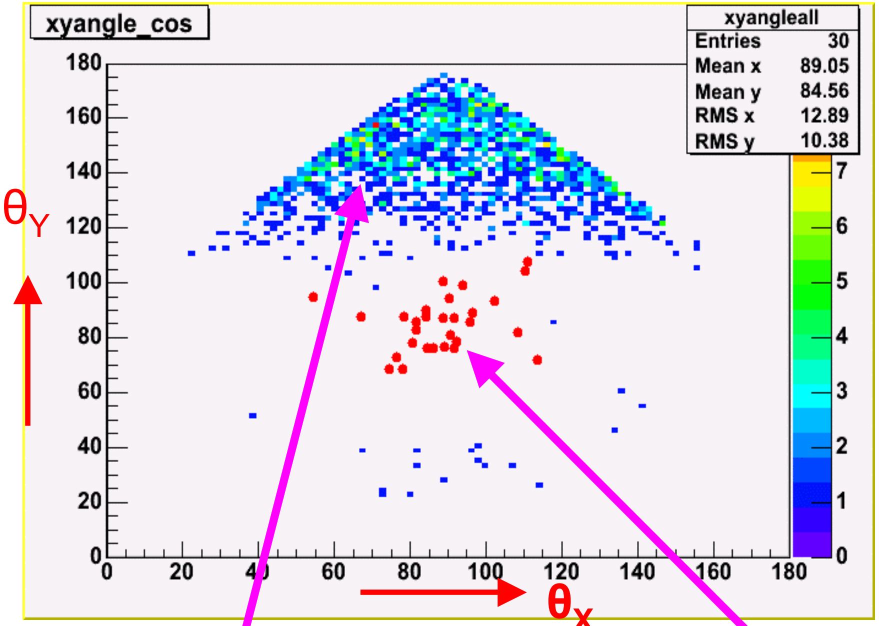


An Example:

14.7 GeV Netrino interaction (HE beam run)

Far Detector: ν-event selection





Timing:

Beam events occur in a 10 μs interval

Cosmics

Neutrino Interactions

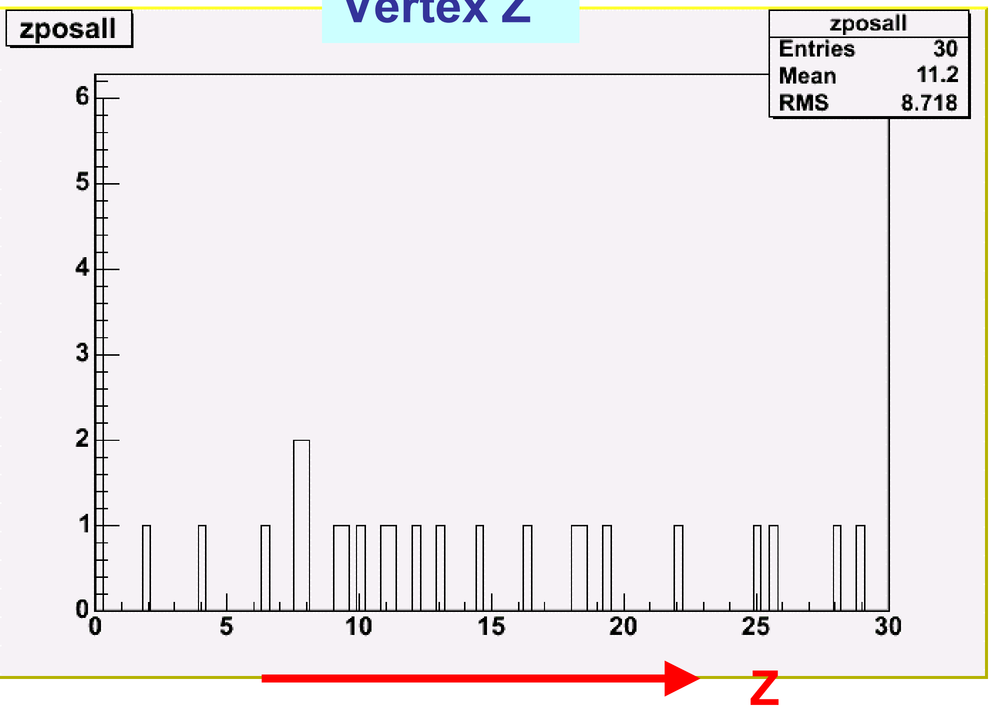
Topology:

Beam events have different direction than cosmics

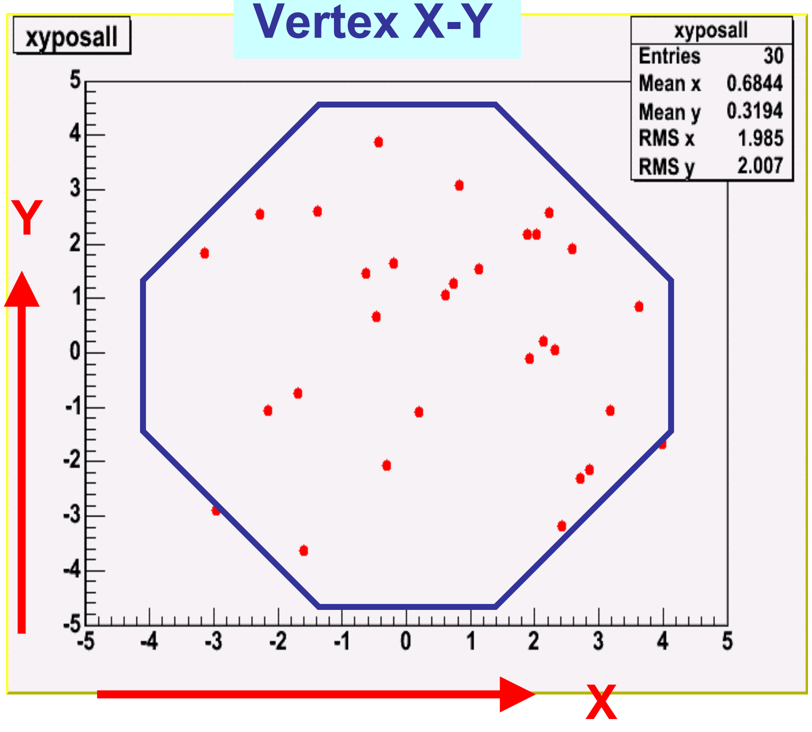
Far Detector: ν-event Analysis

- Event characteristics in agreement with expectations
- Blind Analysis employed in the Far Detector Data

Vertex Z

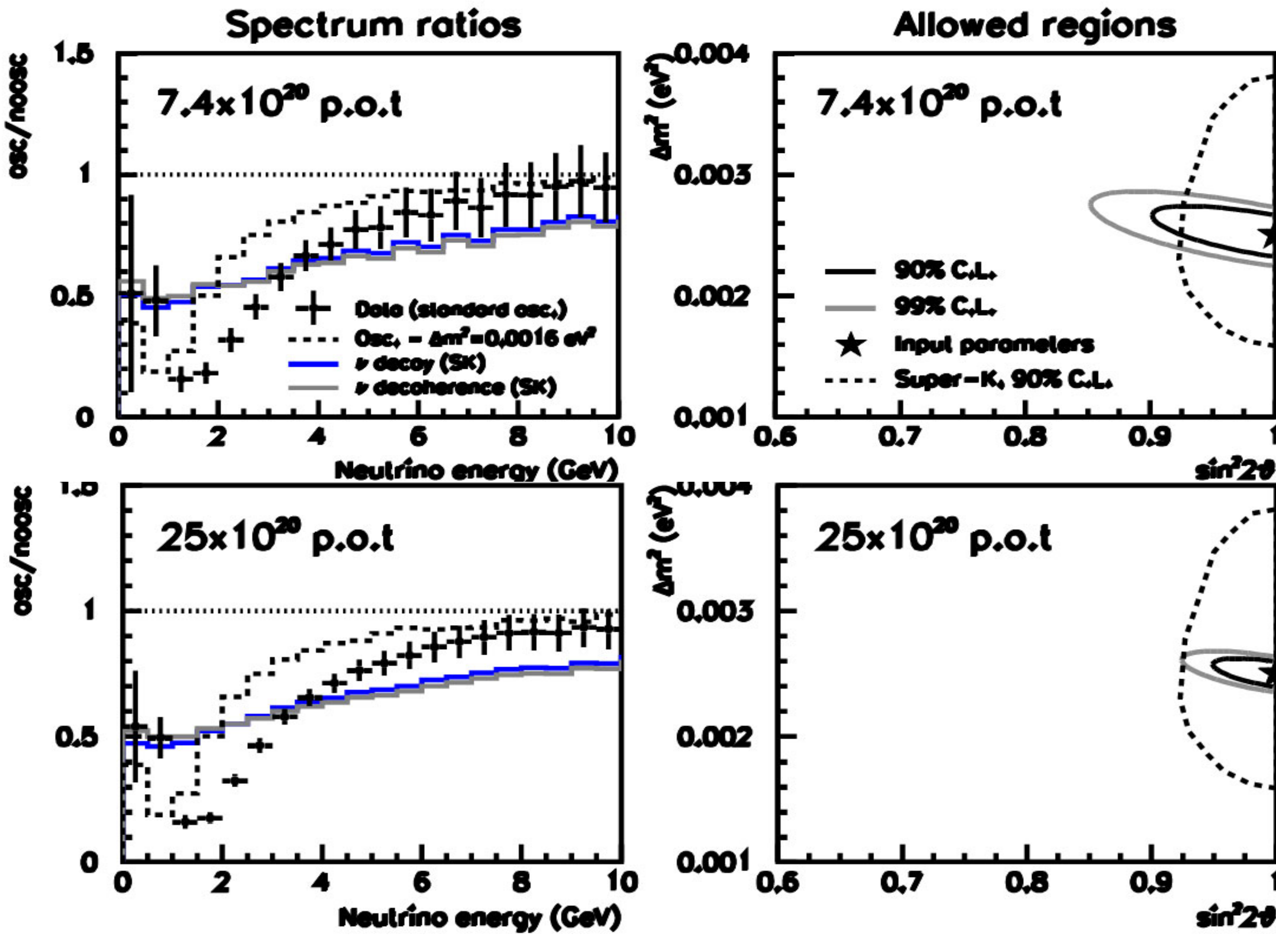


Vertex X-Y



Muon Neutrino Disappearance

MC Prediction for $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$



Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs E_{obs}

MINOS 90% and 99% CL allowed oscillation parameter space.

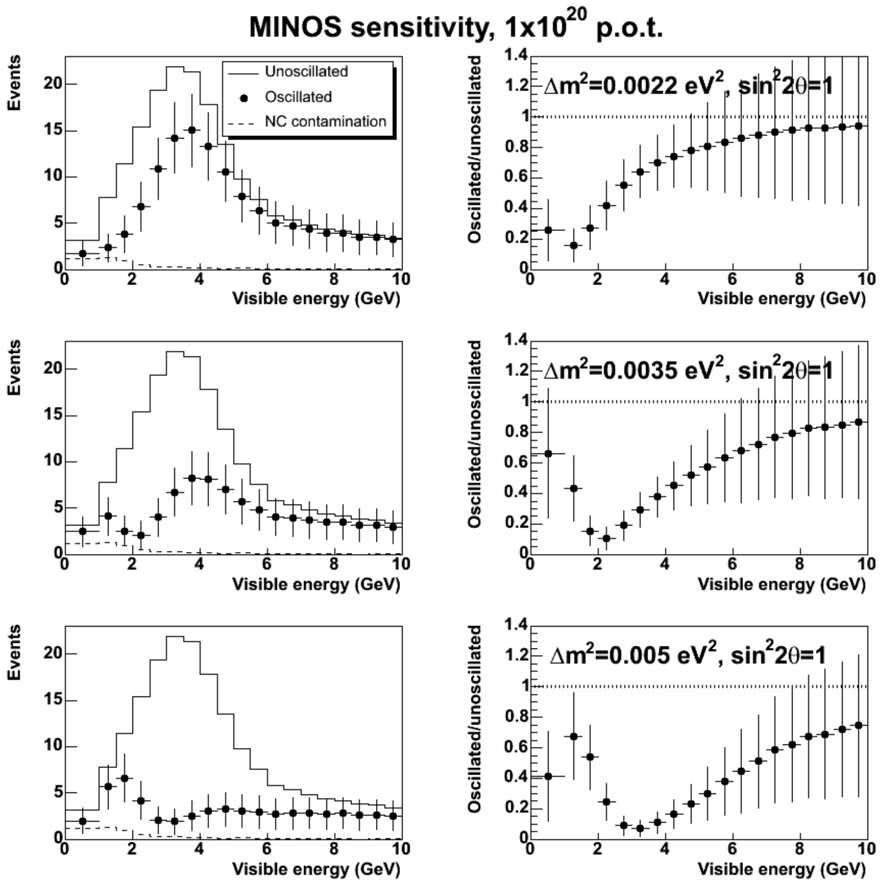
Muon Neutrino Disappearance

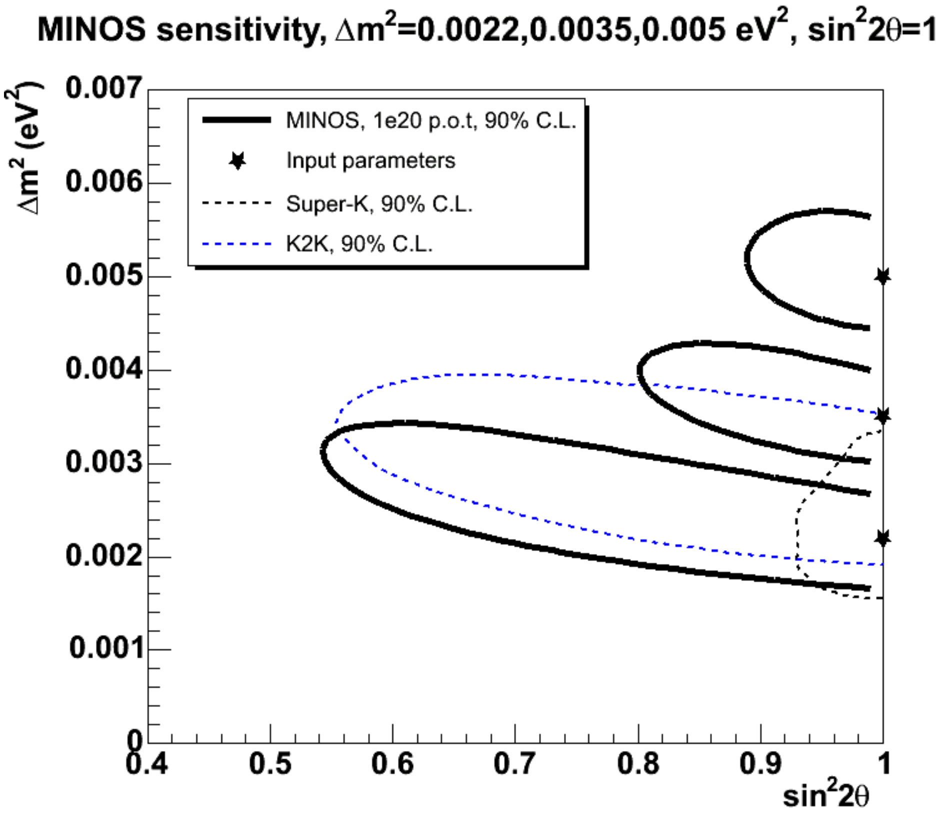
Expected results for 1x 10^{20} POT for three values of Δm^2_{23}

Energy Spectrum Distortion

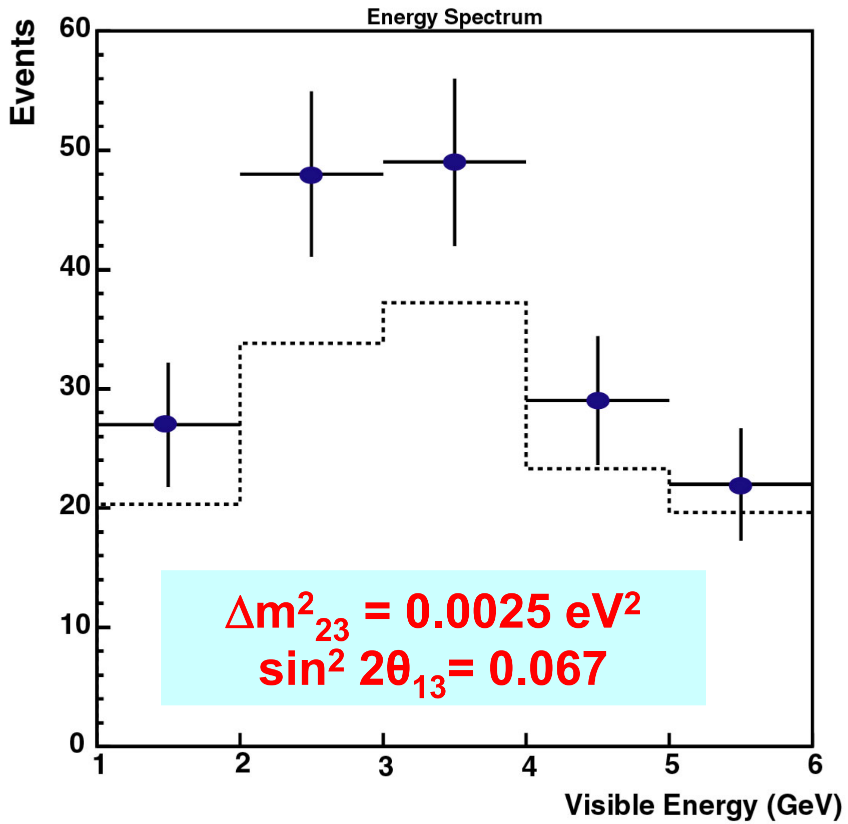
Spectrum Ratio: Oscil/No-Oscil

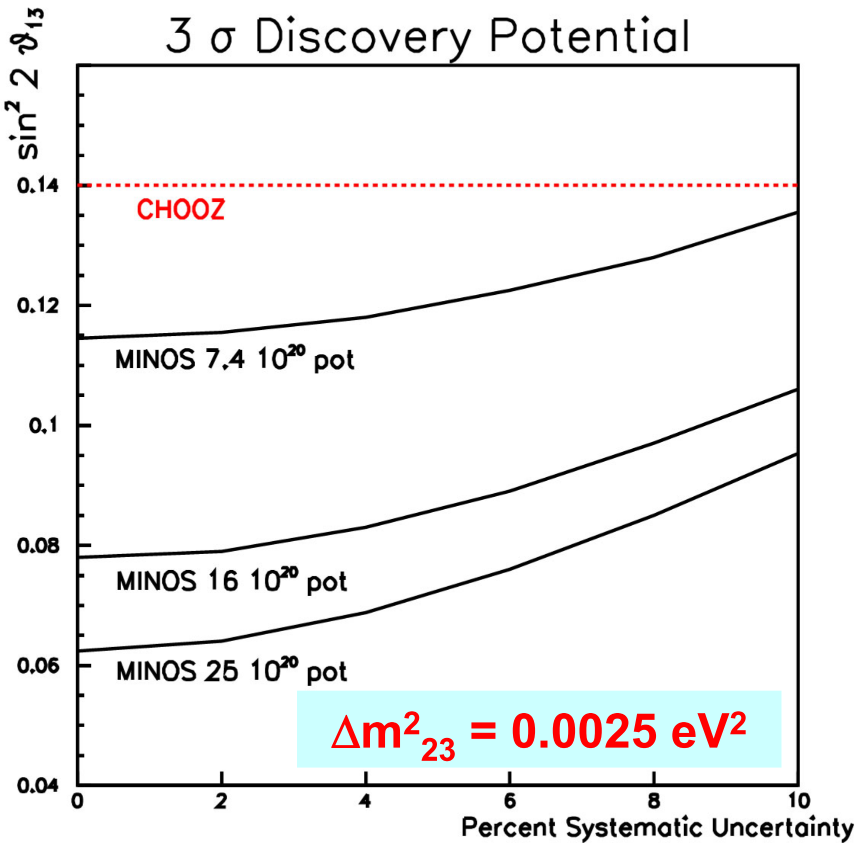
90% Confidence Level Contours





Electron Neutrino Appearance



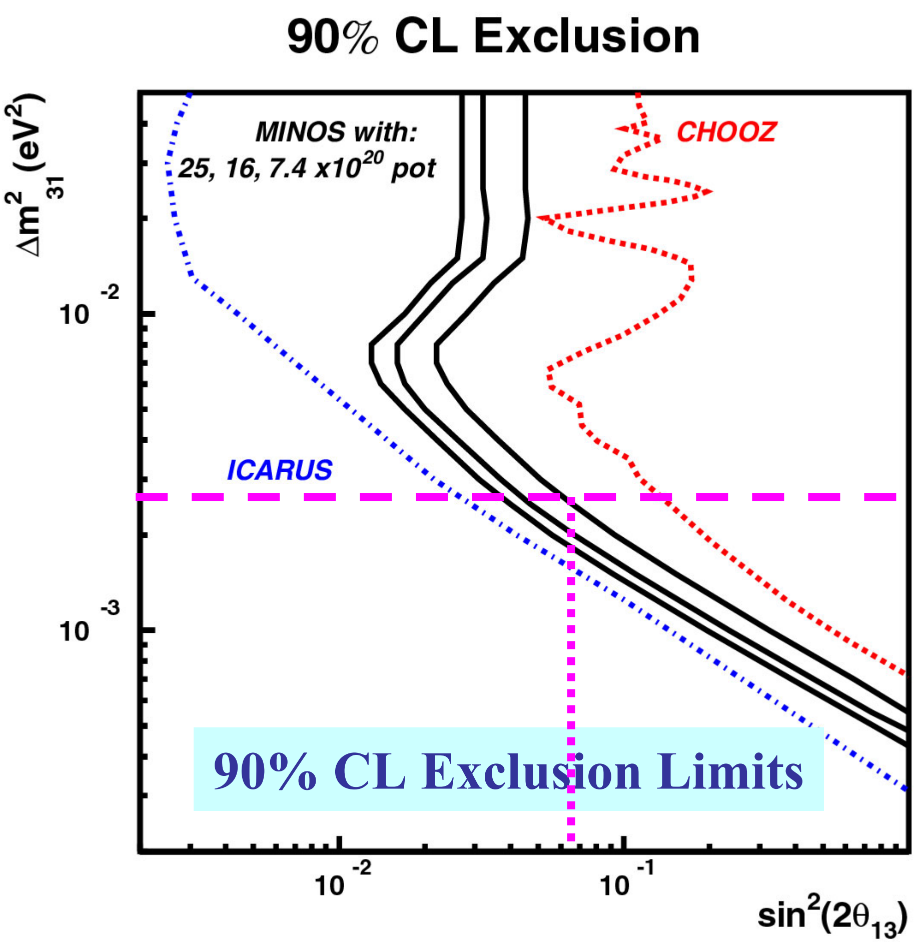


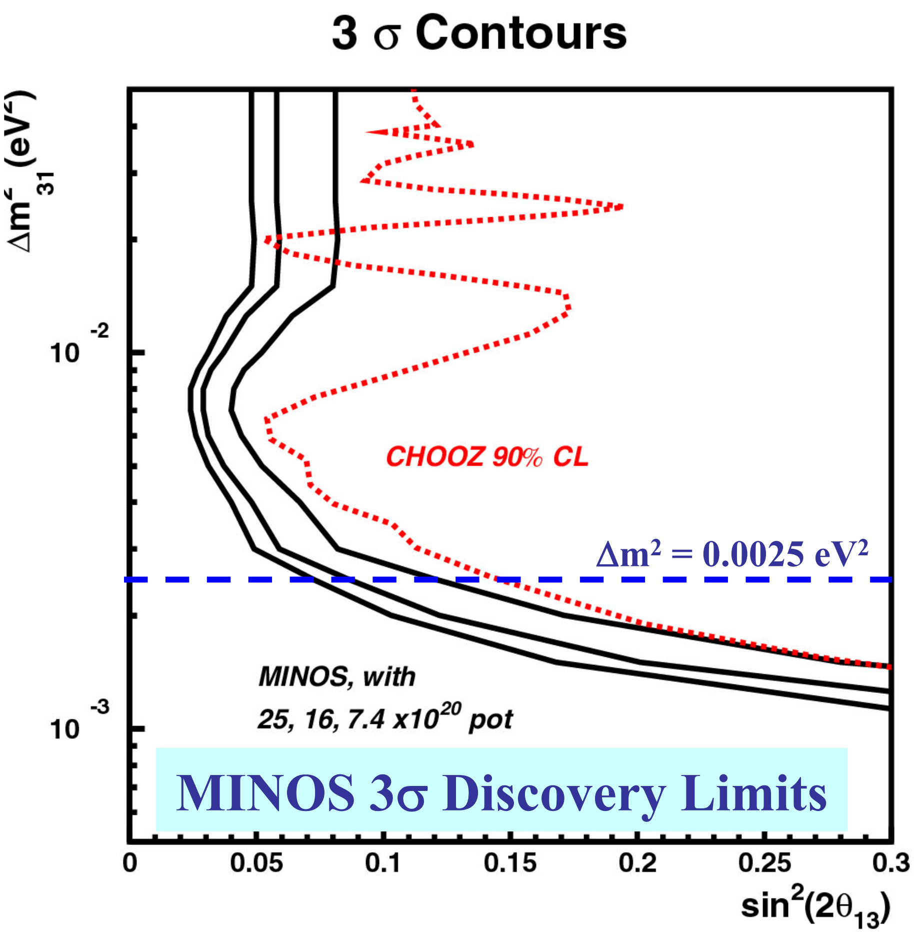
Observed number of events identified as coming from ν_e CC interactions with and without oscillations. 25×10^{20} protons on target.

3 σ discovery potential for three different levels of protons on target and versus systematic uncertainty on the background.

Electron Neutrino Appearance

• MINOS sensitivities based on varying numbers of protons on target





Conclusions

- The MINOS Detectors and NuMI Beam construction and Commisioning have been succesfully completed.
- Collecting Atmospheric Neutrino data since July 2003
- Collecting Accelerator Neutrino Data since March 2005
- Preliminary results of neutrino induced up-going muons
- First Results of FC and PC atmospheric neutrinos: Expect preprint in hep server very soon.
- NuMI beam intensity is continuously improving, expect to have $1.\mathrm{x}10^{20}$ POT by the end of 2005.
- Both MINOS detectors operating satisfactorily
- Near MINOS detector accumulating high statistics
- Far detector data blind analysis
- Expect first physics results from NuMI beam neutrinos in 2006

Acknowledgements

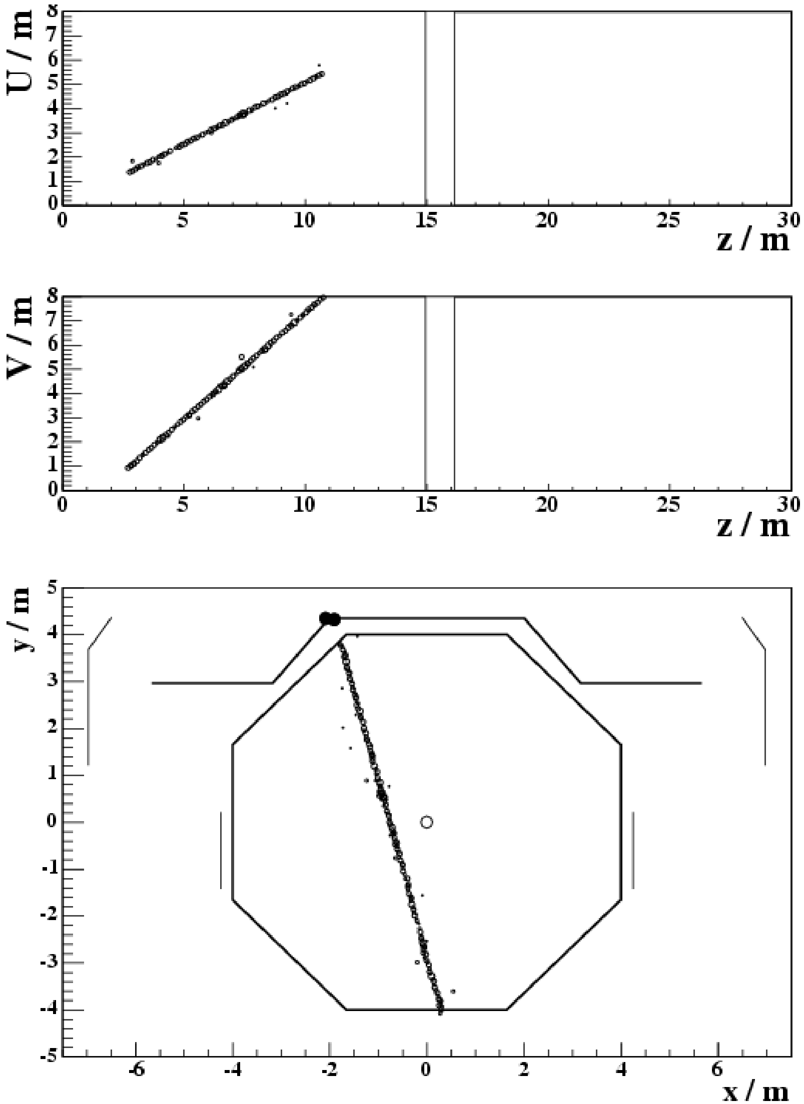
The MINOS Collaboration

Especially:

C. Howcroft, M. Messier, D. Michael, D. Petyt, B. Rebel, N. Saoulidou, M. Thomson, J. Urheim, B. Viren, S. Wojcicki

Backup Slides

Cosmic Ray Muon in MINOS FarDet



Up-going vs down-going muons

In ⊥ incidence: 10 planes ↔ 2 ns

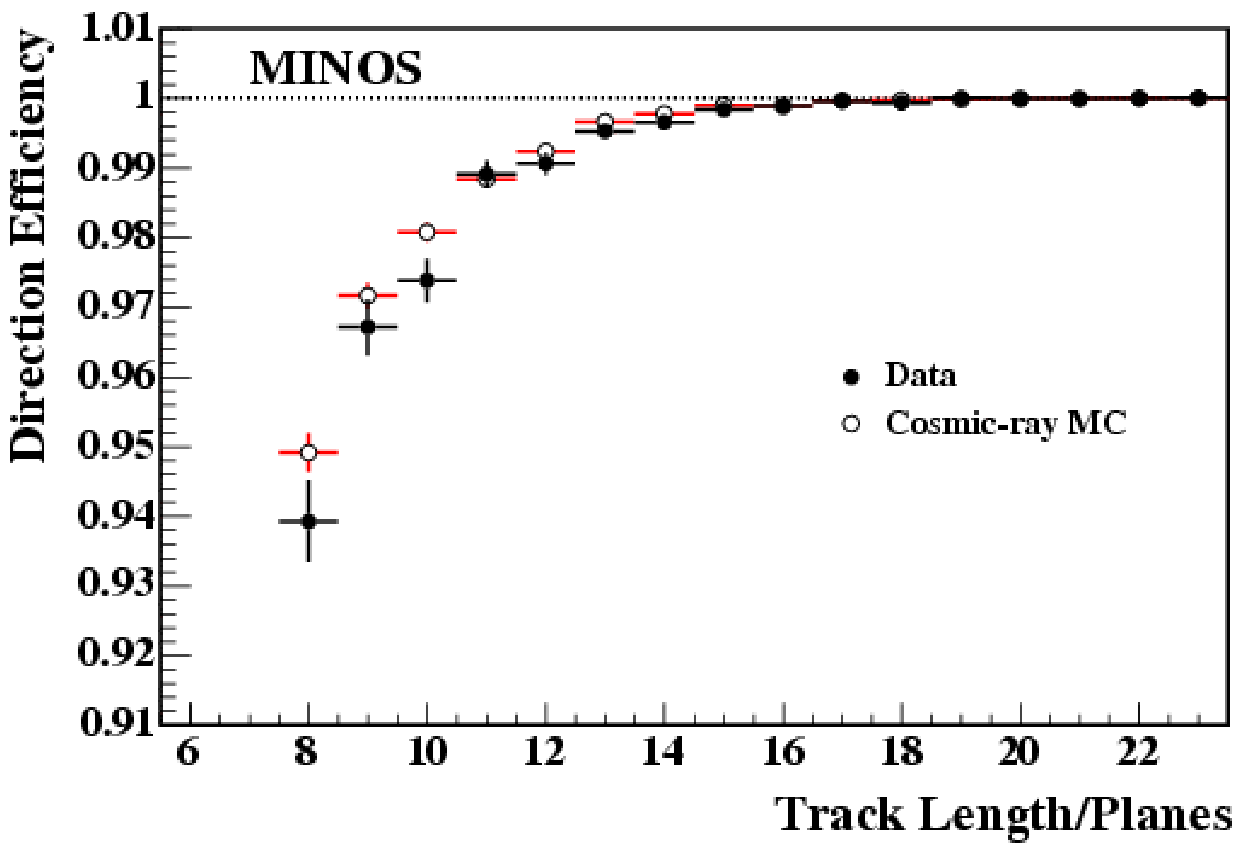
Single hit time resolution: **2.3 ns**

Sense of direction:

- Compare hit times along reconstructed track with up-going or down – going hypothesis.
- Estimate the RMS deviations RMS_{UP}, RMS_{DOWN}
- Choose hypothesis with smallest RMS.
- RMS_{UP} - RMS_{DOWN} ↔ measure of quality of direction determination

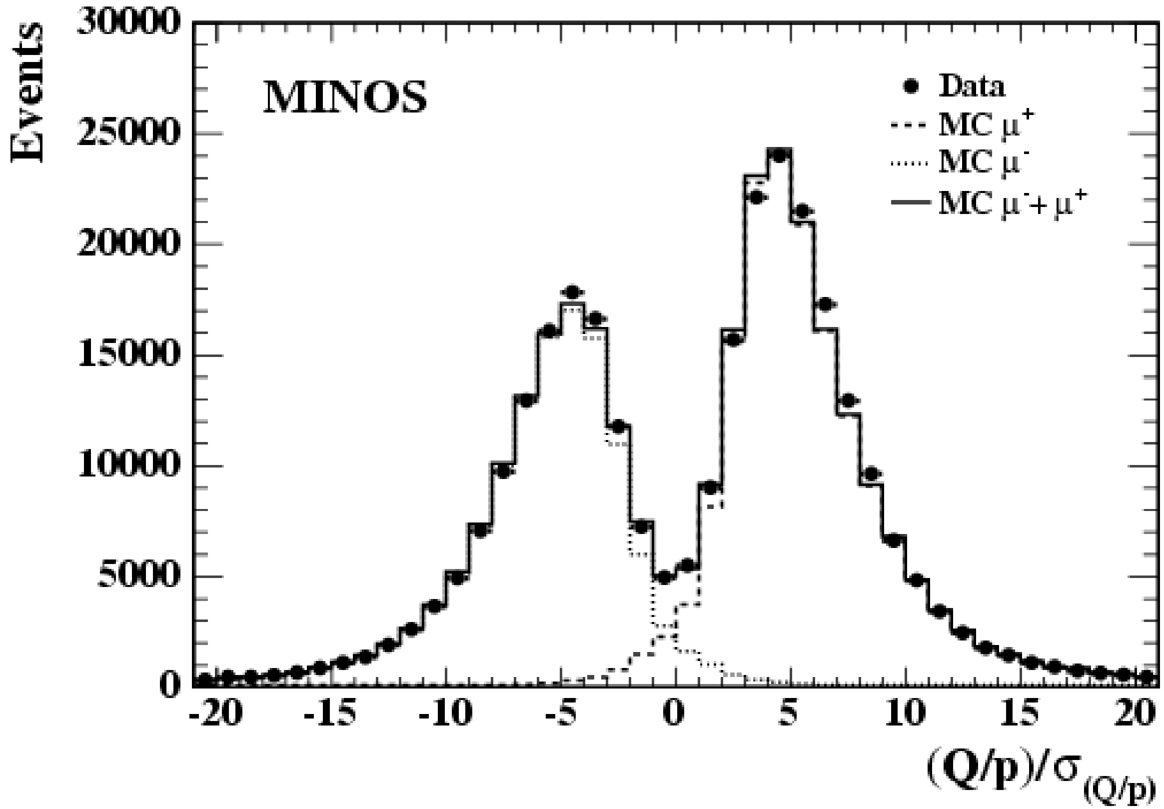
ATMOS Prob Down Stop (Direction Efficiency)

Efficiency of correctly reconstructing stopping muon events as down-going versus number of planes



ATMOS (Q/p)/sigma(Q/p)_Stop

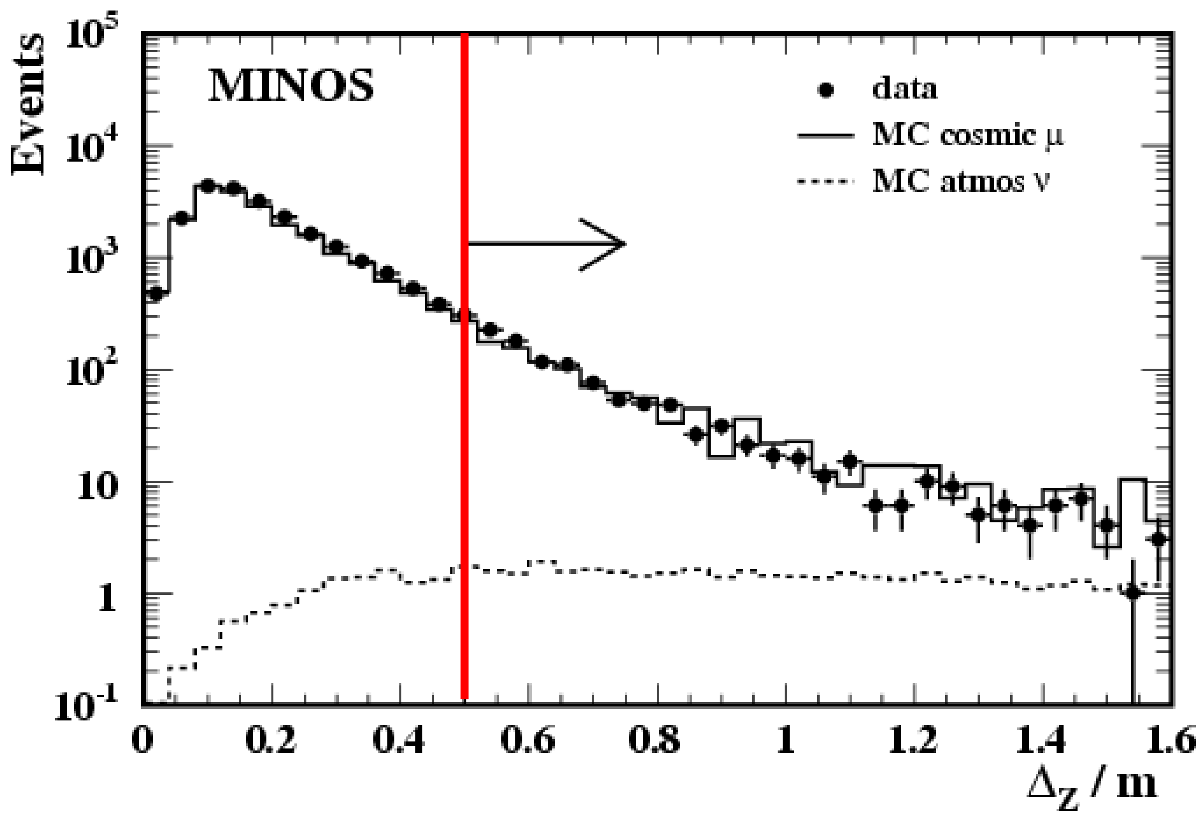
- Charge sign of μ^+/μ^- from curvature
- Use $(Q/p)/\sigma_{Q/p}$
- μ^+/μ^- charge cleanly identified in 0.8 – 10 GeV



ATMOS: C-R Rejection: Trace (z-projection)

Δ_z = z- projection of extrapolated track to outside of detector

Reject track if $\Delta_z < 0.5$ m

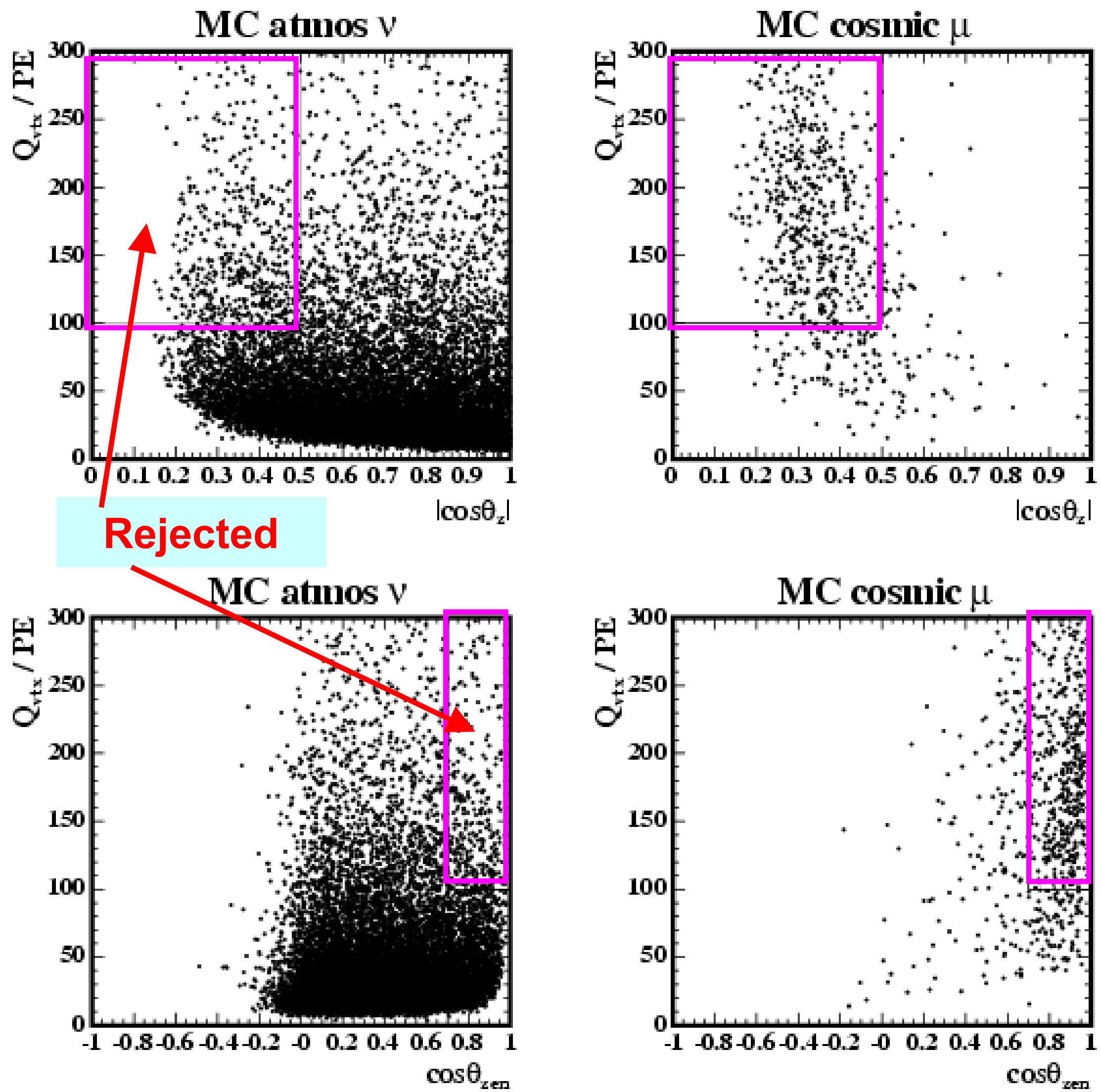


ATMOS: Topology Rejection

- 50% of remaining BGND consists of cosmic-ray muon tracks that bend in the B field and turnover in z-direction.
- Use charge weighted deviations from fitted track in U-z, V-z planes.
- Calculate $<\Delta_{UV}>$ and $<\Delta^2_{UV}>^{1/2}$
- Reject if $<\Delta^2_{UV}>^{1/2} > 0.5$ m
- Reject if $<\Delta_{UV}> > 0.25$ m
- Event vertex = first hit of track with max y
- Δ_R^{max} = max displacement from event vertex of hits with $\pm$ 4 planes. Reject if $\Delta_R^{max} > 1.25$ m
- After the topology cut S:B = 1:5

ATMOS: Vertex Charge/Direction Cut

- After the topology cut S:B = 1:5
- Remaining BGND: CR muon tracks poorly reconstructed.
- Q_{vtx} = max{no PE within ± 4 planes of Vertex}
- Plot Q_{vtx} vs $|\cos\theta_z|$, $\cos\theta_{zen}$
- Reject if Q_{vtx} > 300 PE
- Steep tracks: $|\cos\theta_z| < 0.5$
  $|\cos\theta_{zen}| > 0.7$
  kept if Q_{vtx} < 100 PE



ATMOS: Selection of Upward PC Events

Event Topology

- Reject if Q_{vtx} > 300 PE
- Reject if Δ_R^{max} > 1.25 m

Track timing rms

- Up-going hypothesis (RMS_{UP})
- Down-going hypothesis (RMS_{DOWN})
- Plot ($RMS_{UP} - RMS_{DOWN}$

Require:

- RMS_{UP} < 4.33 ns
- ($RMS_{UP} - RMS_{DOWN}$) < -1.66 ns
- (Remember: single hit time resolution = 2.3 ns)